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THESIS

USING DYNAMIC SUSTAINMENT TO DETERMINE THE IMPACT OF VARYING LEVELS OF RELIABILITY ON FUTURE COMBAT SYSTEMS MAINTENANCE REQUIREMENTS

by

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December 2006

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13. ABSTRACT (maximum 200 words)

The primary purpose of this thesis is to provide analysis for future reliability studies. This thesis assesses the value of the Dynamic Sustainment simulation model as a logistics modeling tool and demonstrates data analysis techniques that can potentially be applied to model results. The secondary purpose is to explore the impact on the maintenance system of varying levels of platform reliability as part of an ongoing effort to provide the Office of the Secretary of Defense with credible analysis for future combat system reliability.

The effects of a crew repair team having a high or low repair capability; having a fast or slow spare parts delivery speed; having high, medium, or low system reliability; and high or low numbers of mechanics was measured on maintenance man-hours required at the end of a 72-hour scenario. Twenty-four treatments with varying levels of each factor were designed and imposed on four combat arms brigades. The fourth brigade had 70 percent more vehicles than the other three.

Significant effects of all factors except the number of mechanics were found with interaction between those factors. Spare parts delivery speed was ranked high in terms of significance followed by crew repair capability. Slow delivery speed reduced maintenance. Low reliability produced the most maintenance man-hours.

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USING DYNAMIC SUSTAINMENT TO DETERMINE THE IMPACT OF VARYING LEVELS OF RELIABILITY ON FUTURE COMBAT SYSTEMS MAINTENANCE REQUIREMENTS

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The primary purpose of this thesis is to provide analysis for future reliability studies. This thesis assesses the value of the Dynamic Sustainment simulation model as a logistics modeling tool and demonstrates data analysis techniques that can potentially be applied to model results. The secondary purpose is to explore the impact on the maintenance system of varying levels of platform reliability as part of an ongoing effort to provide the Office of the Secretary of Defense with credible analysis for future combat system reliability.

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EXECUTIVE SUMMARY

The primary purpose of this thesis is to provide some analysis which can be used for comparison in future reliability studies. Additionally, this thesis will assess the value of the Dynamic Sustainment model as a logistics modeling tool and demonstrate potential data analysis techniques that can be applied to model results. The secondary purpose is to explore the impact on the maintenance system of varying levels of platform reliability as part of an ongoing effort to provide the Office of the Secretary of Defense with credible analysis for key performance parameter #5 which is to analyze the effects on reliability on future combat systems.

A division of the U.S. Army's Training and Doctrine Command's Analysis Center (TRAC) located at Ft. Lee, Virginia will use the research from this study as a point of departure for next year's reliability analysis. Next year in support of FCS system reliability analysis, TRAC expects TRAC-WSMR, a division of TRAC located in White Sands, New Mexico to run a simulation using the Combined Arms Support Task Force Evaluation Model (CASTFOREM) model for at least one additional scenario; and TRAC-FLVN, a division of TRAC in Ft. Leavenworth, Kansas to run a simulation using a different model, Vector-In-Commander (VIC), for at least two additional scenarios. The division located at Ft. Lee, VA (TRAC-LEE) will have a new generic 72-hour sustainment scenario by next spring. Force structure, assumptions, and data will have changed also; however, the basic structure for next year's analysis should be similar to prior analysis. Applying DS to this analysis in 2006 will significantly improve future analysis and help to validate the DS model.

The study used an ANOVA design. There were four independent variables: probability of crew repair (with two levels: 60 and 80 percent), reliability (with three levels: 0.5, 1, and 2 times the performance requirement), number of mechanics (with two levels: 0.5 and 2 times the planned number), and spare parts delivery speed (with two levels: 0.5 and 2 times the planning speed).

Reliability is measured in mean miles between failures (MMBF), which can be used to calculate mean time between failures (MTBF) if the average distance traveled is known. MTBF data was scaled by 0.5, 1, and 2 to arrive at each level. The spare parts delivery speed is scaled similarly. There was one dependent variable: maintenance man-hours (MMH) required during the scenario. MMH required is a measure of the scheduled load of work for the mechanics at a combat repair team.

Significant effects of all factors except the number of mechanics were found with interaction between those factors. Spare parts delivery speed ranked highest in terms of significance followed by crew repair capability and reliability. Slow delivery speed reduced maintenance. Since MMH required is a measure of the scheduled workload for the mechanics and work cannot be scheduled without the necessary parts, when parts arrive at a slower rate, less maintenance is scheduled and therefore required. Low reliability produced the most MMH. DS simulates the operations of a typical repair center and presumably can be applied to real-world operations.

I. INTRODUCTION TO SUSTAINMENT ANALYSIS IN THE ARMY

A. BACKGROUND

Providing adequate materiel support in the field during war or conflict is a challenging endeavor even for the well-equipped and fully funded force. Ensuring timely parts delivery from myriad sources, securing reliable component parts, and having properly trained personnel in sufficient numbers to conduct repairs are some of the logistics challenges which must be overcome to sustain a force which is far away from its primary base. Compounding the logistics problem is that “In the Army's acquisition and procurement processes for new weapon systems, the reliability, maintainability, and supportability requirements frequently are traded for increased lethality and survivability or reduced item prices.”[1]“Three consecutive Army Chiefs of Staff have proclaimed the need for a revolutionary transformation in military logistics.”[2]

Foremost in the Army transformation plan is the development of the future force This force of the future will include light, medium, and heavy formations. The major difference between the three formations will be the number of forces in each. The ability to operate with more than one type of formation should result in greater strategic versatility and agility. More versatility and agility could free the Army of its reliance on the M-1 Abrams tank and the M-2 Bradley infantry fighting vehicle.

The M-1 Abrams and the M-2 Bradley have been the workhorses for the Army for decades. Unfortunately, transporting and supporting these assets requires enormous lift capability and significant repair capability. Switching to a lighter, more reliable force would significantly increase the Army’s fighting effectiveness. The Army would like to increase its effectiveness by transforming/modernizing itself into a future force equipped with a well-coordinated group of technologically sophisticated manned and unmanned ground and aerial systems called Future Combat Systems (FCS). FCS is an all-encompassing modernization effort within the overall Army transformation plan.

1 “Asymmetric Sustainment: The Army's Future” Colonel Larry D. Harman, [www.almc.army.mil/ALOG/issues/JulAug03/commentary_asymmetric.htm.], December 8, 2006

2 Ibid.

These systems will give the joint team under the Joint Forces Commander an array of fully responsive capabilities to succeed in both regular and irregular environments.[3]

B. KEY PERFORMANCE PARAMETER #5 -- RELIABILITY

Reliability analysis is the focus of sustainment[4] analysis for FCS in the Office of the Secretary of Defense (OSD) in FY07.[5] A generally accepted measurement for maintenance reliability is mean time between failures (MTBF) of a particular system. For example, if a system fails, reliability analysis is interested in the time remaining until this system fails again.

The Army G3 and the Army Capabilities Integration Center (ARCIC) has tasked the TRAC to address several items in sustainment analysis. One item, FCS key performance parameter # 5, is to "Analyze the impact of varying levels of platform reliability on sustainment requirements."[6] To that end, TRAC is developing a new suite of logistics analysis tools to support analysis for Army and joint transformation. TRAC has developed a stand-alone Dynamic Sustainment maintenance model which replicates the capabilities from the legacy methods and extends those capabilities for future force maintenance sustainment analysis.

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3 The 2006 Army Modernization plan defines modernization as follows: the development and fielding of improved operational capabilities through a combination of organizational restructuring into modular formations, the insertion of new technologies into existing systems and units, and/or the procurement of new systems with improved capabilities. All of these measures must be complemented by effective Soldier and leader training and education in order to reach their full potential.

4 JP 1-02, DOD Dictionary of Military and Associated Terms, 12 April 2001, as amended through 14 April 2006 defines sustainment as “the provision of logistics and personnel services required to maintain and prolong operations until successful mission accomplishment.”

5 O’ Connor states that reliability can be defined as the ability of an item to perform a required function under stated conditions for a stated period of time in Practical Reliability Engineering, 4th ed.,(Wiley, UK, 2002), pp. xxvi.

6 The Defense Acquisition Acronyms and Terms Glossary from the Defense Acquisition University, Fort Belvoir, Virginia, Twelfth Edition, September 2003 defines key performance parameter (KPP) as “Those attributes or characteristics of a system that are considered critical or essential to the development of an effective military capability and those attributes that make a significant contribution to the key characteristics as defined in the Joint Operations Concept. KPPs are validated by the Joint Requirements Oversight Council (JROC) for JROC Interest documents.” On April 28, 2003, the Army announced that the Joint Requirements Oversight Council (JROC) had approved the FCS Operational Requirements Document (ORD); validated the seven FCS Key Performance Parameters (KPPs); delegated non-KPP ORD approval authority to the Chief of Staff of the Army; and approved the Army's plan for iterative JROC program review and KPP updates. Giving KPP approval authority to OSD necessitates that KPP updates be provided to OSD; therefore, all reliability analysis (KPP #5) is to be forwarded to OSD.

The project proposal for the design of DS describes it as an object-oriented maintenance model that can be run either as a standalone model or as a DS module linked to an entity-level combat simulation.[7]

The intended purpose for the DS model is to provide an alternative to the current methods of logistical analysis in the Army. Current methods are time-consuming, manpower intensive, and incomplete. Maintenance analysis does not consider combat situations, and therefore, there has been little analysis of the effect of maintenance on combat scenarios or of operational tempo (OPTEMPO) on reliability. The DS model must now be validated prior to use in actual studies by applying the model to the analysis of a representative problem. Simulation model validation is a way to increase trust in a model's ability to mimic the real world.

TRAC plans to conduct studies of reliability in the near future, so studying how well the DS model mimics real-life sustainment operations is an important area for analysis.

The DS project was commissioned in late 2004 after the maintenance analysis associated with FCS Milestone B Analysis of Alternatives highlighted how taxing and time-consuming current methods of logistics and maintenance analysis were. The maintenance proposal says that current methods "only indirectly represent 'dynamic' sustainment [and] typically there is insufficient time to run this process iteratively so the [System of Systems Availability Model] SoSAM-based availability 'curves' or tables are predicated on previous combat modeling which might not adequately reflect the operating tempo, combat losses, etc . . ." [8] The project originators hoped to not only produce a model "capable of modeling future force (FF) dynamic Sustainment [but also to] increase logistic situational awareness [as well as] improve the common operating picture when linked to F-o-F [force on force] combat models."

The current method for logistical analysis is quite tedious and very time-consuming. As evidence of how tedious this process is, consider the following

7 Dynamic Sustainment Modeling in Support of Battle Command Analysis, project report. August 2004.

8 Ibid.

approach which was used with the VIC model to support Milestone B of the Defense Acquisition Process.

The FCS Milestone B Analysis of Alternatives (AoA)[9] VIC modeling approach was: 1) combat modelers from TRAC [provided the Army Materiel Systems Analysis Activity] AMSAA with operating tempo data (distance traveled, hours operated, rounds fired) from previous modeling which best [reflected] the proposed scenario; 2) AMSAA [adjusted] reliability estimates to reflect the operating tempo, and [adjusted] other scenario specific data; 3) AMSAA [ran] the System of Systems Availability Model (SoSAM), with the adjusted input, for the first combat pulse, and [sent] the results to TRAC-LEE (i.e., number of system aborts, and availability level snapshots for each 4-hour interval); 4) TRAC-LEE [calculated] the number of systems returned to duty during the 1st logistics pause, e.g., a Sustainment Replenishment Operation (SRO) or a Mission Staging Operation (MSO), and [sent] the results back to AMSAA; 5) this process [continued] between AMSAA and TRAC-LEE for each additional combat pulse and logistics pause; 6) at the last combat pulse or logistics pause, TRAC-LEE [re-formatted] the data for the combat model and [sent] the results to TRAC-FLVN; 7) TRAC-FLVN [updated] availability levels in VIC after each four-hour interval, based on the SoSAM results[10]

C. PURPOSE OF THIS THESIS

The primary purpose of this thesis is to provide some analysis which can be used for comparison in future reliability studies. Additionally, this thesis will assess the value of the DS model as a logistics modeling tool and demonstrate potential data analysis techniques that can be applied to model results. The secondary purpose is to explore the impact on the maintenance system of varying levels of platform reliability as part of an ongoing effort to provide OSD with credible analysis for KPP #5. TRAC-LEE will use

9 According to the Defense Acquisition University's Glossary: Defense Acquisition Acronyms and Terms, 12th Edition, July 2005, an AoA is an evaluation of the performance, operational effectiveness, operational suitability, and estimated costs of alternative systems to meet a mission capability. The analysis assesses the advantages and disadvantages of alternatives being considered to satisfy capabilities, including the sensitivity of each alternative to possible changes in key assumptions or variables.

10 Dynamic Sustainment Modeling in Support of Battle Command Analysis, project report. August 2004.

this research as a point of departure for next year's reliability analysis. TRAC expects TRAC-WSMR to run CASTFOREM for at least one additional scenario; and TRAC-FLVN to run VIC for at least two additional scenarios next year in support of this analysis. TRAC-LEE will also have a new generic 72-hour sustainment scenario Operational Mode Summary-Mission Profile (OMS-MP) by next spring. Force structure, assumptions and data will have changed; however, the basic structure for next year's analysis should be similar to prior analysis. Applying DS to this analysis in 2006 will significantly improve future structures and help to validate the DS model.

D. STRUCTURE OF THIS THESIS

Chapter II outlines the method for conducting this study, including some detail of the DS model and the exact configurations that were used for each treatment. Chapter III displays the study results. Chapter IV offers some general discussion. Appendix A is a list of acronyms used in the thesis. Appendix B presents additional charts of MMH data output. Appendix C provides greater amplification of the Defense Acquisition Process as well as information on current Army simulation models mentioned in this thesis.

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II. METHOD FOR CONDUCTING DYNAMIC SUSTAINMENT EXPERIMENT

A. EXPERIMENTAL DESIGN

The study used an ANOVA design. There were four independent variables: probability of crew repair (with two levels: 60 and 80 percent), reliability (with three levels: 0.5, 1, and 2 times the performance requirement), number of mechanics (with two levels: 0.5 and 2 times the planned number), and spare parts delivery speed (with two levels: 0.5 and 2 times the planning speed). Reliability is measured in mean miles between failures (MMBF), which can be used to calculate mean time between failures (MTBF) if the average distance traveled is known. MTBF data was scaled by 0.5, 1, and 2 to arrive at each level. The spare parts delivery speed is scaled similarly. MMH required is a measure of the scheduled load of work for the mechanics at a combat repair team.

B. SYSTEMS USED – FCS PLATFORMS

The terms systems, vehicles, and platforms are used interchangeably throughout this report. FCS can be referred to as specific types of vehicles and/or platforms.

DS can be used to simulate any system's response, but this study used the FCS family of systems and some existing systems. The "18 +1+1 Systems Overview," from the Program Manager for FCS Brigade Combat Team lists 18 manned and unmanned, ground and aerial platforms. This study considers the 8 manned ground vehicles, but only 2 of the unmanned vehicles. There are 1064 vehicles across the four brigades in the simulation. What follows is a description of each of the vehicles in the study.[11]. Table 1 details the unmanned ground vehicles. Table 2 gives the manned ground vehicles.

11 The descriptions provides rely heavily on the "FCS 2005 Flipbook," the "18 +1+1 Systems Overview," and Army Magazine's "Hooah Guide to Future Combat Systems."

Unmanned Ground Vehicles (UGV)

Platform		Mission	Armament/Payload	Gross Weight
MULE	Multifunction Utility/Logistics and Equipment Vehicle	3 variants: MULE-T for transport of equipment and/or supplies;ARV-A-L armed to support dismounted infantry; MULE-CM to detect/neutralizeAT mines	1900 lbs for cargo, electro-optical/infrared sensors, laser range finder/designator, and network nodes as required.	2.5 tons
ARV	Armed Robotic Vehicle	Provides reconnaissance capability / over-watching LOS/BLOS fires / semi-autonomous / network node	Javelin and Mk-44 30mm (Assault variant);FCS-common close support weapon (RSTA variant)	C-130 transportable

Table 1. Unmanned Ground Vehicles[12]

12 Global Security. "FCS 2005 Flipbook,"[http://www.globalsecurity.org/military/library/report/2005/050000-fcs2005flipbook.pdf]. December 10, 2006.

Manned Ground Vehicles (MGV)

	Platform	Mission	Armament	Gross Weight	Crew
C2V	Command and Control Vehicle	TransportableProvides battle command, control and communications for the Tactical Commander / network node.	XM-307 25mm	C-17 & C-130 Transportable	2 Common Crew; 2 Integrated Crewmen +2 Dismounted Scouts
RSV	Reconnaissance and Surveillance Vehicle	Conducts streamlined acquisition, discrimination of multiple target sets, and provides a dynamic hunter-killer capability/ network node	MK44 30/40mm	C-17 & C-130 Transportable	2 Common Crew + 4 Dismounted Scouts
ICV	Infantry Combat Vehicle	Provides the mobility for 11 personnel(two-man crew and nine-man infantry squad)on the battlefield / network node.	MK44 30/40mm	C-17 & C-130 Transportable	2 Crew + 9 Infantry
MCS	Mounted Combat System	Provides offensive maneuver to close with and destroy enemy forces including both Line of Sight and Beyond-Line of Sightcapabilities / network node	Light weight 120 mm main gun; XM307 25 mm	C-17 & C-130 Transportable	3 Crew
NLOS-C	Non-Line-Of-Sight Cannon	Provides networked, extended-range targeting and precision attack of point and area targets in support of the FCS equipped units / network node	155mm (primary armament), XM-307 25mm	C-17 & C-130 Transportable	2 Crew
NLOS-M	Non-Line-Of-Sight Mortar	FCS network node providing short-range fires support to assault units	120mm Mortar(primary armament), XM-307 25mm	C-17 & C-130 Transportable	4 Crew
MV-E/T	Medical Vehicle - Evacuation/Treatment	Manned Maneuver Sustainment Platform that provides the medical system within both the FCS equipped units. Has a common chassis with two types of interchangeable modules: Evacuation (MV-E); Treatment (MV-T); networked medicine. Accommodation for 4 litters or 6 ambulatory casualties.		C-17 & C-130 Transportable	3 to 4 Crew
FRMV	FCS Recovery and Maintenance Vehicle	Recovery and Maintenance System for FCS BCT,Critical Component of Combat Repair Team.Additional Passenger space for 2 recovered passengers.	XM-307 25mm	C-17 & C-130 Transportable	3 Crew

Table 2. Manned Ground Vehicles[13]

[13] Global Security. "FCS 2005 Flipbook," [http://www.globalsecurity.org/military/library/report/2005/050000-fcs2005flipbook.pdf]. December 10, 2006.

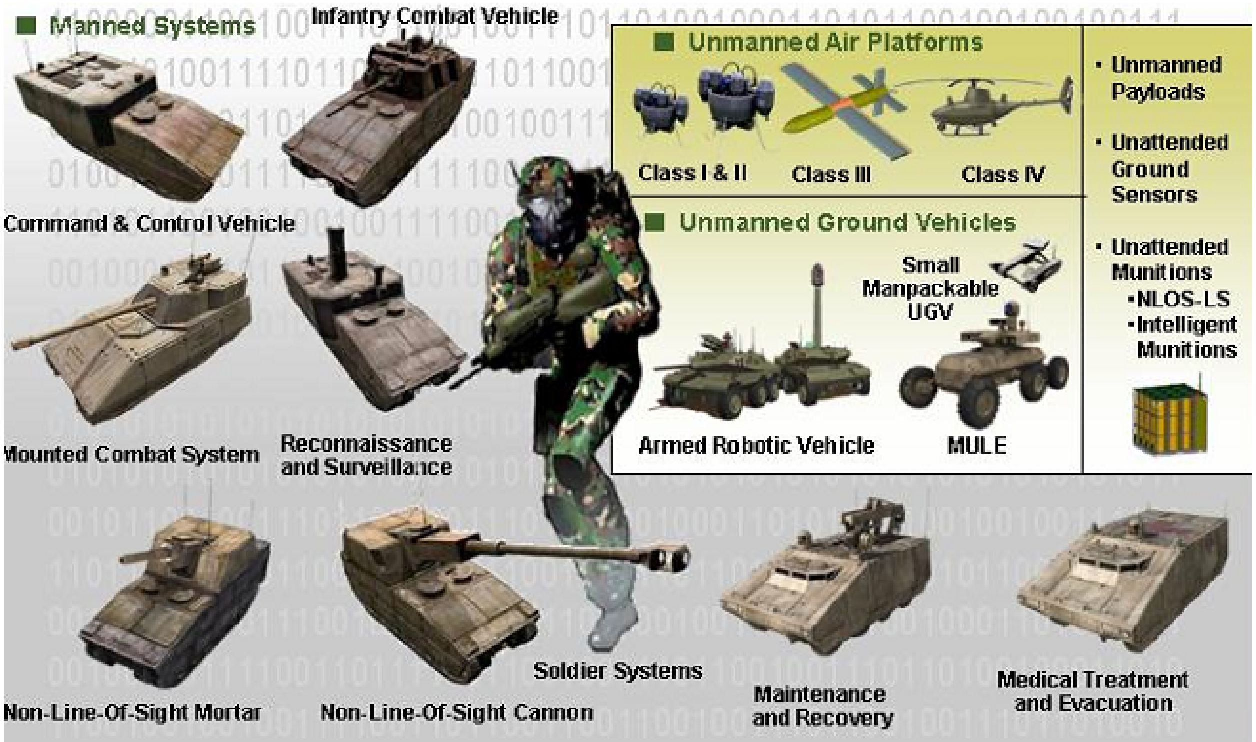

Figure 1. FCS Combat Systems Manned and Unmanned Vehicles[14]

1. ADDITIONAL SYSTEMS USED – EXISTING

The OSD, scenario FCS OMS-MP, includes five systems which are currently in use today. Those systems are the Heavy Expanded Mobility Tactical Truck (HEMTT), the High Mobility Multipurpose Wheeled Vehicle (HMMWV), a Family of Medium Tactical Vehicles (FMTV), the TPQ-36, and the TPQ-64 Sentinel. The first three platforms are vehicles. The last two are radar systems. These five platforms comprise 559 of the platforms in the simulation, 74 in each of the first, second, and third combined arms brigades, and 222 in the rear combat arms brigade. Figures 2 through 6 are displays of the existing platforms.

[14] Global Security. "FCS 2005 Flipbook," [http://www.globalsecurity.org/military/library/report/2005/050000-fcs2005flipbook.pdf]. December 10, 2006.

Figure 2. Heavy Expanded Mobility Tactical Truck[15]

Figure 3. High Mobility Multipurpose Wheeled Vehicle (HMMWV)[16]

Figure 4. Family of Medium Tactical Vehicles (FMTV)[17]

15 http://www.army.mil/fact_files_site/hemtt/index.html, December 2006.

16 http://www.army.mil/fact_files_site/hemtt/index.html, December 2006.

17 Ibid.

Figure 5. AN/TPQ-36 Fire Finder Radar[18]

Figure 6. AN/MPQ-64 Sentinel[19]

2. Force Structure

The force structure to support this simulation has four combat arms brigades with vehicle types, vehicle numbers, and mechanics as detailed in Tables 3 and 4. Each combat repair team consists of both automotive and communications type mechanics. The first three combat arms brigades (CAB) have the same system types, the same number of vehicles, and the same number of mechanics. Table 3 gives the system types and numbers of systems (count) in combat arms brigades 1-3. The fourth combat arms brigade, the rear combat arms brigade, differs in the types and numbers of vehicles it has as well as the percentage of crew repair capability that the combat repair team making repairs for this unit possesses. Table 4 gives the system types and the number of systems in the rear combat arms brigades. The rear combat arms brigade has the following vehicles: ICV, C2V, NLOS-LS, MV, FRMV, MULE-RT, HEMTT, and

18 http://www.raytheon.com/products/tpq36/, December 2006.

19 http://www.thalesraytheon.com/us-anmpq64.htm#, December 2006.

HMMWV. See Tables 1 and 2 for manned and unmanned vehicle descriptions. Additionally, it has 162 more vehicles than the other three brigades. It has 395 vehicles and the other CABs have 233. Moreover, roughly 60 percent of the vehicles in the rear CAB cannot be repaired by the crew in the rear combat repair team. Finally, there are roughly twice as many mechanics in the rear combat repair team.

System Type	**Count**
ICV	33
C2V	10
RSV	10
MCS	20
NLOS - M	8
NLOS - LS	12
NLOS - C	6
MV -E	5
MV - T	2
FRMV	3
ARV-RSTA	9
ARV - L	6
ARV - A	6
MULE - T	18
MULE - CM	10
MULE - RT	1
HEMTT Wrecker	1
HEMTT LHS - Maint	1
HEMTT LHS - Supply	30
HEMTT CARGO	3
HMMWV Spt - Maint	1
HMMWV Spt - Supply	9
HMMWV C2	19
HMMWV Knight	2
FMTV	6
TPQ-36	1
TPQ-64	1
Total Vehicles	**233**

Table 3. Force Structure Used in Combat Arms Brigades 1-3

System Type	Count
ICV	3
C2V	19
NLOS - LS	24
MV -E	4
MV - T	4
FRMV	1
MULE - RT	3
HEMTT Wrecker	6
HEMTT LHS - Maint	2
HEMTT LHS - Supply	111
HMMWV Spt - Maint	3
HMMWV Spt - Supply	122
HMMWV C2	62
HMMWV Ambulance	6
HMMWV Treat	2
HMMWV Knight	1
FMTV	12
Forklift 10K	2
Forklift 4K	8
Auto Mechanic	39
Comm Mechanic	8
Total Vehicles	**395**

Table 4. Force Structure Used in Rear Combat Arms Brigade

C. DYNAMIC SUSTAINMENT MODEL

The DS model captures the OPTEMPO data of the forces in a simulation[20]; generates component failures based on system use; represents combat damage to vehicles and mechanics; and prioritizes which systems are repaired when workloads exceed capacity.

DS is a stand-alone, constructive, closed-loop, stochastic[21], discrete event model[22] which uses Simkit[23] as the simulation engine. DS is object oriented using the

20 A simulation is a computer program used as a model for some other system of interest. In a simulation model the entities are described by numerical (coded) attributes. The state of the simulation includes the values for all of its attributes as well as what is known about the future. From "Graphical Model Structures For Discrete Event Simulation" Lee W. Schruben Proceedings of the 1992 Winter Simulation Conference ed, J, J, Swain, D. Goldsman, R. C. Crain, and T R Wilson.

21 The following definitions from www.Wikipedia.org help explain the model description: Dynamic simulations model changes in a system in response to (usually changing) input signals. Stochastic models use random number generators to model the chance or random events; they are also called Monte Carlo simulations. December 19, 2006.

Java programming language which requires the Java virtual machine (JVM) 1.5 and higher. DS will generate random variates from several distributions. This study uses only the triangle and the exponential time-varying distributions.

Figure 7 is a schematic of the inputs and outputs in DS. Depending on the length of the scenario and the number of replications, it could be anywhere from a few seconds to several hours before the output files are fully generated. DS is not interactive. It is a closed-loop model. All changes to the setup of the scenario must be completed prior to loading the input file. Once the scenario has begun, it cannot be changed without canceling the run and beginning anew.

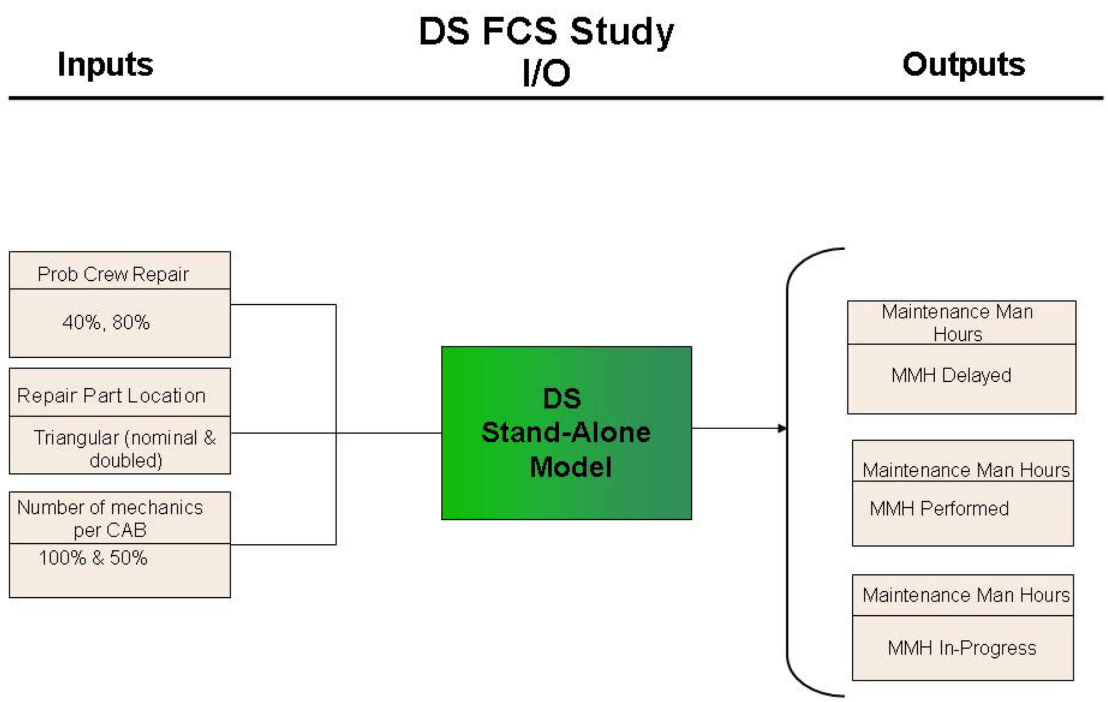

Figure 7. Dynamic Sustainment Model Inputs/Outputs[24]

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22 A discrete event simulation (DE) manages events in time. Most computer, logic-test and fault-tree simulations are of this type. In this type of simulation, the simulator maintains a queue of events sorted by the simulated time they should occur. The simulator reads the queue and triggers new events as each event is processed. “Graphical Model Structures For Discrete Event Simulation” Lee W. Schruben Proceedings of the 1992 Winter Simulation Conference ed, J, J, Swain, D. Goldsman, R. C. Crain, and T R Wilson.

23 http://diana.gl.nps.navy.mil/Simkit/. December 1, 2006.

24 Ruck, J. “Introduction to the Dynamic Sustainment Model” PowerPoint presentation, August 15, 2006.

1. Distributions in DS

Possible distributions for generating random variates in DS are exponential, time varying exponential, constant, gamma, or triangle[25].These distributions can be used to generate random failure and repair times. They can also be used to generate the time at which a vehicle might be recovered as well as the delivery time for spare parts.

2. Java Classes in DS

DS has a collection of Java classes (objects). For the standalone version, the simulation events are initially driven by the MTBFFaultGenerator and the CombatDamage classes. The design of the model is captured in an event graph.

a. Reading the DS Event Graph

Figures 8 and 9 are sections of the DS event graph. These two graphs model the actions of the MTBFFaultGenerator and the CombatDamage classes, respectively. The structure of the event graph has significance. The dotted rectangular box surrounding the elliptical shapes signifies that the contents within are a Java class that is a subclass of the SimEntityBase object in Simkit. Simkit is a package used to create discrete event simulations in Java 2.

A SimEntityBase is a basic object in Simkit that is also a SimEvent listener in that it can listen to the SimEvent scheduled by other SimEntityBase objects. The elliptical shape represents separate simulation events [26](SimEvents) handled within the Java class/object. The solid arrow extended from one event to another denotes that while processing the first event, the second event is scheduled. Where there are words written underneath the arrows, these represent conditions to be met before the next event is scheduled. For example, in the MTBFFaultGenerator class, the ClearFailure event is processed. There is a solid arrow extending to the CauseFailure event with

25 Triangle Distribution: Often when there is no data for an event, one can generate random variates using the triangle distribution. The triangle distribution is a friendly distribution in that generating data from it often requires that one get acquainted with the subject matter expert. This person with the most experience gives what has been in there experience the best, most likely, and worst occurrence of a particular event.

26 Schruben defines an event as any situation where the state of the system might possibly change. He further notes that in a discrete event dynamic system all changes in state occur at discrete instants of time. "Graphical Model Structures For Discrete Event Simulation" Lee W. Schruben Proceedings of the 1992 Winter Simulation Conference ed, J, J, Swain, D. Goldsman, R. C. Crain, and T R Wilson.

"failure delay" written underneath the arrow. This means that "ClearFailure schedules the CauseFailure event with a failure delay." Another example is in the CombatDamageGenerator class; there the CauseDamage event schedules a CauseKKill event if KKill occurs. The dotted arrow shows that an event can be cancelled. For example, in the MTBFFaultGenerator class, the NotifyInactive event cancels the CauseFailure event scheduled previously.

To drive the simulation, another Simkit SimEntityBase subclass called FailureMode listens to the MTBFFaultGenerator and CombatDamageGenerator objects/classes, and the FailureMode itself in turn, listens to and is heard by SimEvent listeners (SimEntityBase objects) of the DS model. For the MTBFFaultGenerator, it also listens to FailMode for events such as ClearFailure, NotifyActive, and NotifyInactive.[27]

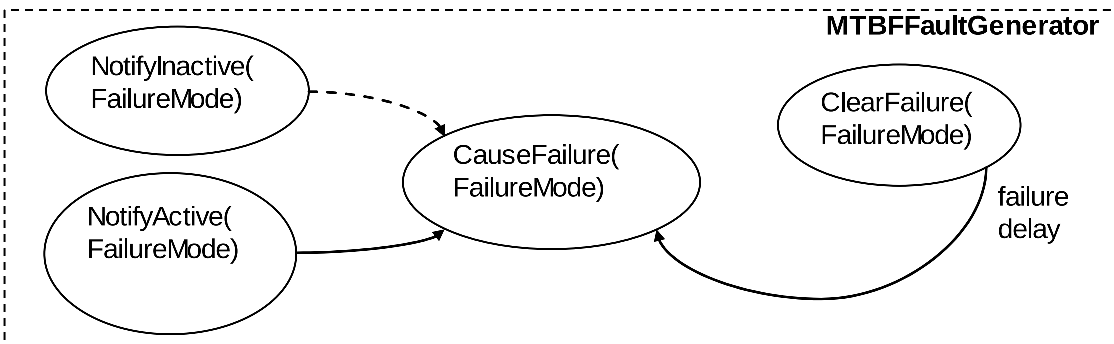


Figure 8. MTBFFaultGenerator class

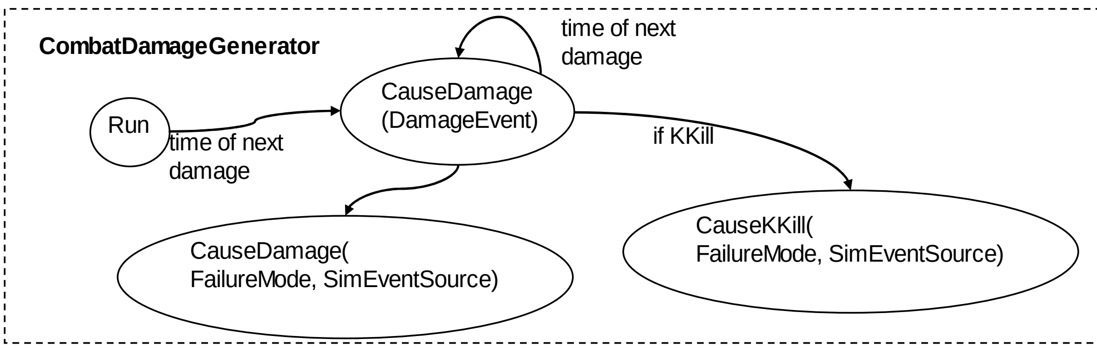


Figure 9. CombatDamageGenerator class

27 Wu, J., Roland and Associates contractor, email November 29, 2006.

3. Description of Data – Combat Scenarios

Data sets to support this analysis were available from the last update the Army provided to OSD. TRAC provided data from high resolution combat models for scenarios in Southwest Asia and Northeast Asia along with data from a generic 72-hour sustainment scenario based on the FCS OMS-MP. The "OMS" for the FCS is a sequence of missions for three Major Combat Operations (MCOs). This study only considers the FCS OMS-MP data set.

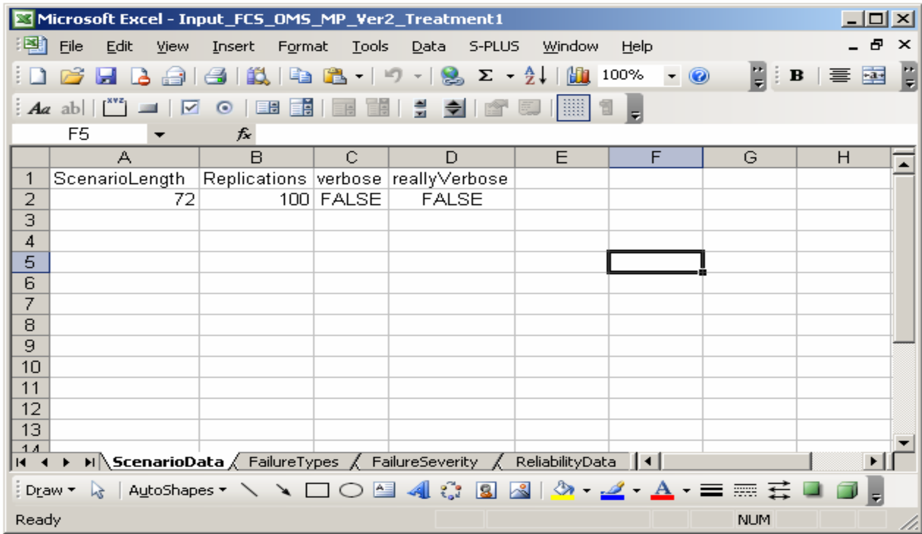
4. Standalone Model Input File

There are fourteen worksheets in the standalone model input file for DS. Table 5 details the purpose of each worksheet. Figures 10 and 11 display examples of the scenario data and reliability data input file worksheets, respectively. By simply changing the inputs in row 2 of the ScenarioData worksheet, the user can adjust the length of the scenario or adjust the number of replications.

Worksheet	Purpose	Notes
Scenario Data	Sets scenario length and number of replications or runs to perform	
FailureTypes	Determines the kinds of failures that can happen to a system.	Failure types = auto, comm, arm, and mobility
FailureSeverity	Sets the level of failure	Types = SA (System Abort), EFF (essential function failure), NEFF (non-essential function failure), PROG (prognostics)
ReliabilityData	Determines the rate at which systems fail.	
ForceStructure	Sets the number and types of systems in the scenario and includes mechanics	
Combat	Schedule for when the given Units are considered in combat.	Combat periods for the same unit cannot overlap
DeferredMaintenance	Used to determine which types of failure severities will be deferred during combat	
RepairUmpire	Used to define the distributions of time to repair.	Order of entries is important. The entries for a given RepairUmpire will be searched in order until a match is found to determine the repair time distribution.
RecoveryUmpire	Allows the user to specify the source of recovery assets, the distribution of recovery time, and the rule for which recoveries are deferred during combat.	
Consumable	Used to define the distribution for the delivery time of spares	
RepairManual	Names the repair parts and repair assets to be used by the Repair Commander to repair a failure.	
RepairCommander	Defines Repair Commanders for unit repair	Each unit in the ForceStructure sheet should be assigned to one RepairCommander with CrewRepair TRUE and one with CrewRepair FALSE
CombatDamage	Schedules combat damage by unit or system at a specific time during the scenario	
Output	Establishes destination file for writing output and allows the user to set which of the possible outputs he/she would like to obtain from the simulation.	Scenario length must coincide with period for some data loggers.

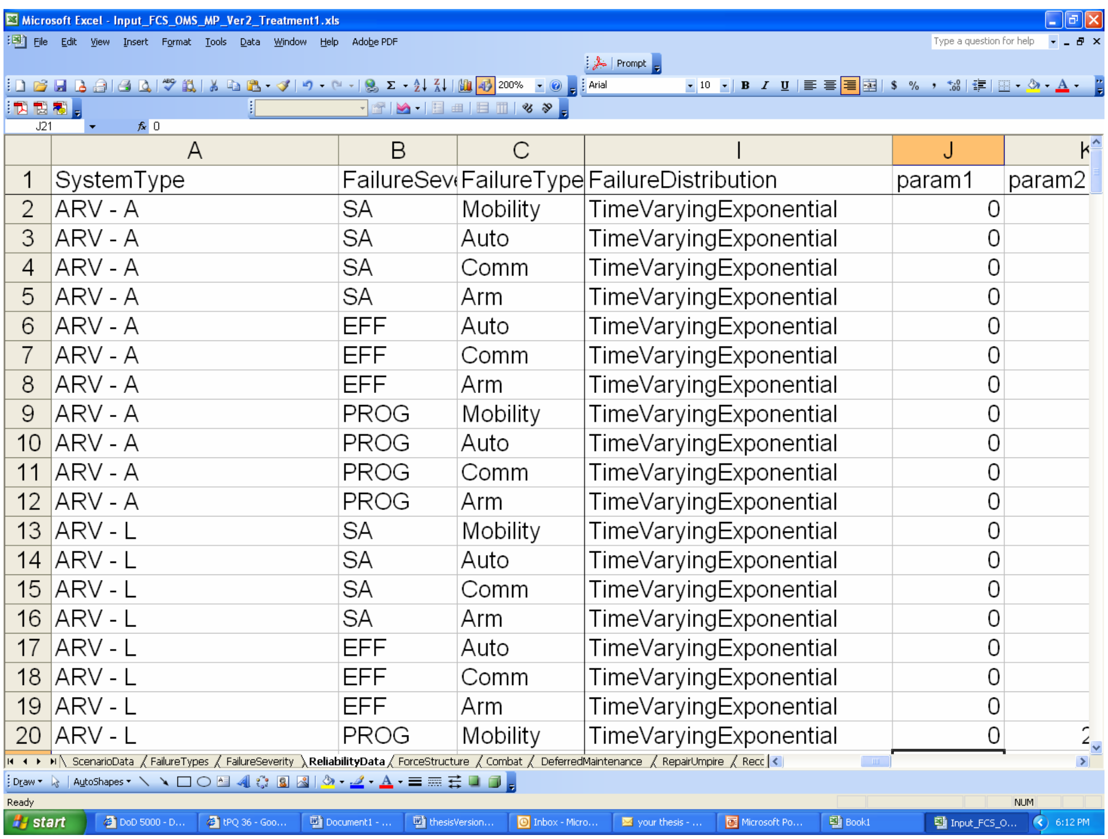
Table 5. DS Worksheets for Standalone Model

a. *Example Worksheets from Input File*



ScenarioLength	Replications	verbose	reallyVerbose
72	100	FALSE	FALSE

Figure 10. Scenario Data Worksheet



SystemType	FailureSev	FailureType	FailureDistribution	param1	param2
ARV - A	SA	Mobility	TimeVaryingExponential	0	
ARV - A	SA	Auto	TimeVaryingExponential	0	
ARV - A	SA	Comm	TimeVaryingExponential	0	
ARV - A	SA	Arm	TimeVaryingExponential	0	
ARV - A	EFF	Auto	TimeVaryingExponential	0	
ARV - A	EFF	Comm	TimeVaryingExponential	0	
ARV - A	EFF	Arm	TimeVaryingExponential	0	
ARV - A	PROG	Mobility	TimeVaryingExponential	0	
ARV - A	PROG	Auto	TimeVaryingExponential	0	
ARV - A	PROG	Comm	TimeVaryingExponential	0	
ARV - A	PROG	Arm	TimeVaryingExponential	0	
ARV - L	SA	Mobility	TimeVaryingExponential	0	
ARV - L	SA	Auto	TimeVaryingExponential	0	
ARV - L	SA	Comm	TimeVaryingExponential	0	
ARV - L	SA	Arm	TimeVaryingExponential	0	
ARV - L	EFF	Auto	TimeVaryingExponential	0	
ARV - L	EFF	Comm	TimeVaryingExponential	0	
ARV - L	EFF	Arm	TimeVaryingExponential	0	
ARV - L	PROG	Mobility	TimeVaryingExponential	0	

Figure 11. Reliability Data Worksheet

5. Modified Sample Output File

The MMH output files retrieved from DS give four values for each repair depot mechanic for the specified time. For example, in 1CRT, there are maintenance man-hours required (MMH Required), maintenance man-hours performed (MMH Performed), maintenance man-hours delayed (MMH Delayed) and maintenance man-hours in progress (MMH In progress) for both automotive and communications mechanics. There should be 32 values total for each time: four values for each of four depots for each of two types of mechanics. Table 6 displays the last four MMH Delayed values for the communications mechanics as well as the first four MMH In progress values for the automotive mechanics.

replication	time	value	loggerName	requiredAssetType	repairCommander	propertyName	observations
Summary	72	15.91	MMH	Comm Mechanic	REARCRT RepairDepot	MMH Delayed	100
Summary	72	0	MMH	Comm Mechanic	1CRT RepairDepot	MMH Delayed	100
Summary	72	0	MMH	Comm Mechanic	3CRT RepairDepot	MMH Delayed	100
Summary	72	0	MMH	Comm Mechanic	2CRT RepairDepot	MMH Delayed	100
Summary	72	2.314	MMH	Auto Mechanic	3CRT RepairDepot	MMH In progress	100
Summary	72	0	MMH	Auto Mechanic	REARCRT RepairDepot	MMH In progress	100
Summary	72	2.461	MMH	Auto Mechanic	1CRT RepairDepot	MMH In progress	100
Summary	72	1.832	MMH	Auto Mechanic	2CRT RepairDepot	MMH In progress	100

Table 6. Output for Maintenance Man-hours from Dynamic Sustainment

D. PROCEDURE

Each treatment for this experiment is a specific combination of factors and their associated levels. The intent of this study is to examine the impact of four factors on maintenance requirements. Each factor has a number of levels: three levels for reliability, two levels for the spare parts delivery speed, two levels for the probability of crew repair capability for a failure, and two levels for the number of mechanics. This study takes an exhaustive look at all the treatments which arise from possible combinations of the four factors (i.e. 3 x 2 x 2 x 2 = 24).

1. Matrix of Factors

Table 7 is a matrix of factors used in the 24 treatments in this study. The treatments are in groups of 8 and correspond to their associated reliability. For example, treatments 1-8 have Reliability = 0.5. The first column gives the crew

repair capability associated with each treatment. The second column shows how the spare parts delivery speed was scaled. The remaining columns detail the actual number of automotive and communications mechanics there were at each combat arms brigade (CAB). Normal operating numbers for mechanics at each of the first 3 CABs are 18 automotive and 3 communications. When these numbers are scaled by 0.5 and 2, they become 9 and 2, and 36 and 6, respectively. The same scaling method is used for the mechanics in the rear combat repair team. Ordinarily, there are 39 automotive and 8 communications mechanics on the rear team.

Reliability = .5

	Repair Capability	Delivery Time for Spares	Mechanics for 1CAB, 2CAB, & 3CAB Auto Mechanic	Comm Mechanic	Mechanics for REAR Auto Mechanic	Comm Mechanic
Treatment 1	0.8	0.5	9	2	20	4
Treatment 2	0.8	2	9	2	20	4
Treatment 3	0.8	0.5	36	6	78	16
Treatment 4	0.8	2	36	6	78	16
Treatment 5	0.6	0.5	9	2	20	4
Treatment 6	0.6	2	9	2	20	4
Treatment 7	0.6	0.5	36	6	78	16
Treatment 8	0.6	2	36	6	78	16

Reliability = 1

	Repair Capability	Delivery Time for Spares	Mechanics for 1CAB, 2CAB, & 3CAB Auto Mechanic	Comm Mechanic	Mechanics for REAR Auto Mechanic	Comm Mechanic
Treatment 9	0.8	0.5	9	2	20	4
Treatment 10	0.8	2	9	2	20	4
Treatment 11	0.8	0.5	36	6	78	16
Treatment 12	0.8	2	36	6	78	16
Treatment 13	0.6	0.5	9	2	20	4
Treatment 14	0.6	2	9	2	20	4
Treatment 15	0.6	0.5	36	6	78	16
Treatment 16	0.6	2	36	6	78	16

Reliability = 2

	Repair Capability	Delivery Time for Spares	Mechanics for 1CAB, 2CAB, & 3CAB Auto Mechanic	Comm Mechanic	Mechanics for REAR Auto Mechanic	Comm Mechanic
Treatment 17	0.8	0.5	9	2	20	4
Treatment 18	0.8	2	9	2	20	4
Treatment 19	0.8	0.5	36	6	78	16
Treatment 20	0.8	2	36	6	78	16
Treatment 21	0.6	0.5	9	2	20	4
Treatment 22	0.6	2	9	2	20	4
Treatment 23	0.6	0.5	36	6	78	16
Treatment 24	0.6	2	36	6	78	16

Table 7. Matrix of Factors for Treatments 1-24

The input data file from TRAC-LEE contained data based on a 72-hour scenario. The only worksheets from this Excel input file that were modified to

conduct this experiment were those entitled ScenarioLength, ReliabilityData, Consumable, ForceStructure, and Output. All other worksheets remained unchanged.

The worksheet ScenarioLength was modified to set the number of replications to 100 and the scenario length to 72 hours.

The worksheet ReliabilityData contained the columns that were adjusted to vary both reliability and the probability of crew repair. Reliability was varied by scaling the MTBF. Rather than adjusting each individual failure (note parameter 2 and parameter 4) by different percentages, both parameters were scaled by 0.5, 1, and 2. The intention was to determine the impact of half as many, the usual number, or twice as many failures in a 72-hour period. In short level 0.5 equates to low reliability, level 1 relates to medium reliability, and level 2 is high reliability.

For probability of crew repair, the data under column heading ProbCrewRepairReliability was assigned one of two levels: 0.8 or 0.6 to represent an 80 or 60 percent probability that the crew is capable of repairing the failure. The initial input data file from TRAC showed an 80 percent repair capability as desirable. During the process of approving this experimental design, TRAC-LEE suggested a lower bound of 0.6, offering that this repair capability level was more likely to be achievable.

For the probability of a spare at CAB (Combat Arms Brigade), column headings param1, param2, and param3 under the Consumable worksheet were scaled by 0.5 and 2. The effect of such scaling was to simulate the effect of delivery service half as slow as usual in the case when the parameters are multiplied by 2 (0 to 640 hrs) or twice as fast when the parameters are multiplied by 0.5 (0 to 160 hrs).[28]

28 The plan to scale a triangle produced random variate in the above mentioned fashion was discussed with Dr. Arnie Buss, the SIMKIT developer. He said that there was no issue with this plan, saying "It turns out for the triangle distribution, you can simply scale *all* three values to have a multiplier effect on the mean while leaving the variance untouched. For example, if the base case is triang(10.0, 20.0, 12.0), the mean is (10.0 + 20.0 + 12.0)/3 = 14.0 and the variance is (100.0 + 400.0 + 144.0 - 200.0 -240.0 - 120.0)/18 = 14.0/3. A triang(5.0, 10.0, 6.0) would have half the mean (7.0) with the same variance, while triang(20.0, 40.0, 24.0) would have twice the mean (28.0) and again the same variance." Arnie Buss, email, October 31, 2006.

Similar methodology applies to the number of mechanics. Under the ForceStructure tab of the input data file, in the column heading called Count are the rows labeled 1CRT, 2CRT, 3CRT, and REARCRT, representing the first combat repair team, the second combat repair, and so on. Each of these rows is set to half the usual number for the first level and twice the usual number for the second level. For example, for each of the first three combat repair teams the usual number of auto and communications mechanics is 18 and 6, respectively. For level one, the number of mechanics is 9 for auto mechanics and 3 for communications mechanics.

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III. RESULTS

A. ANALYSIS

A cursory analysis of the required MMH by treatment using Figure 12 below provides some intuitive insights, but is of limited use beyond verifying a few expected patterns. The effects of varying crew repair capability and the number and type of mechanics assigned to each combat repair team are not as evident from inspecting the chart as the effects from reliability and spare parts delivery speed (discussed below).

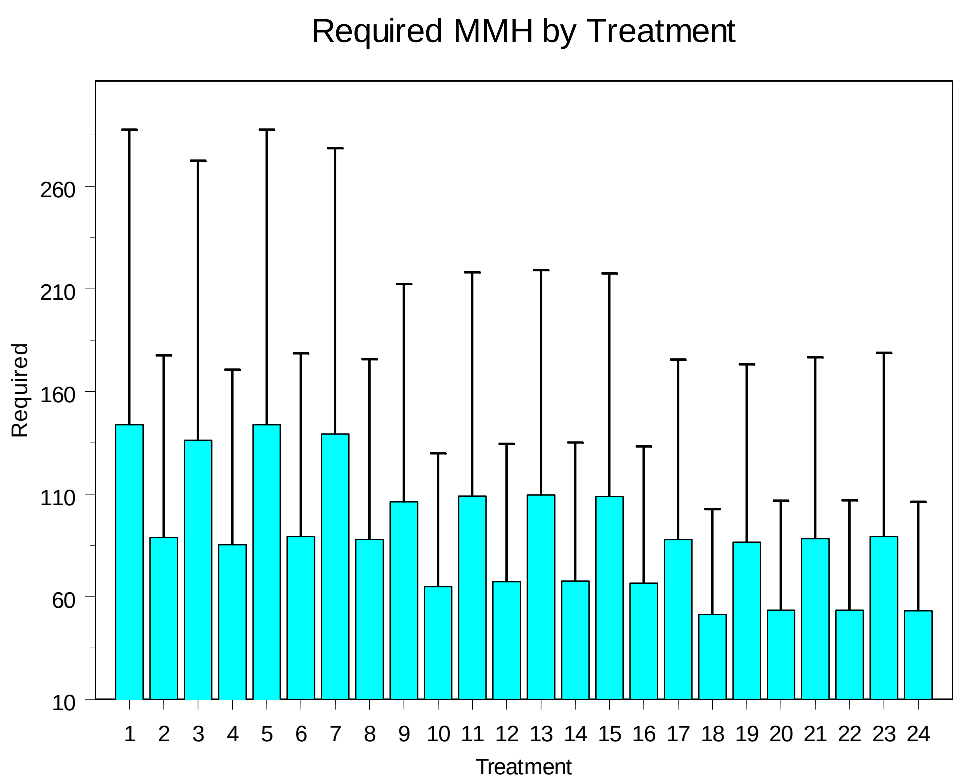

Figure 12. Automotive Maintenance Man-hours Required at the Rear Combat Arms Brigade

There are 70 percent more vehicles in the rear combat repair team than any of the other three combat repair teams. The difference in the number of vehicles assigned is somewhat offset by a greater apportionment of mechanics to the rear combat repair team. Figure 12 depicts the MMH required by treatment for automotive mechanics in the rear combat repair team. Not surprisingly, there

is a distinct pattern to the data in Figure 12 resulting from the differing factor levels of the treatments. Treatments 1-8 require the most maintenance; treatments 17-24 the least maintenance; and treatments 9-16 fall between the two extremes. This stair step pattern reflects the three reliability levels in the experimental design. Recall from Table 7 that the treatments with the greatest reliability were treatments 17-24. Naturally, they would have the least required maintenance. Additionally, it is not surprising that there is a second pattern in the data. The odd- and even-numbered treatments present a second-tier pattern in maintenance required. For example, treatments 2, 4, 6, and 8 are part of the first set of treatments with reliability equal to 0.5 (low). Their required maintenance levels are higher than treatments 10, 12, 14, and 16 (medium); and maintenance levels for these treatments are higher than for the high reliability set (18, 20, 22, and 24). All the even treatments share the same spare parts delivery speed which is 2, or slow. In short, slow delivery time leads to reduced maintenance since the failed systems spend more time waiting for parts. Low reliability requires more maintenance and DS is able to mimic this aspect of real-world maintenance problems. Similar results were found for the communications and automotive mechanics in the other three combat arms brigades.

Appendix B contains additional presentation of data along these lines. The next section using regression analysis is a more rigorous examination of the experimental results.

B. REGRESSION RESULTS

The MMH required data were separated into four data sets. All data sets were categorized by type of mechanic (i.e. automotive or communications). Data from the first three brigades, which are identically equipped and configured, were combined into two data sets called AutoFront and CommFront, depending on the type of mechanic. The other two data sets, AutoRear and CommRear, represent those MMH associated with the combat repair team in the rear combat arms brigade.

1. AutoFront MMH

MMH required at AutoFront was the dependent variable, and reliability, repair capability, spare parts deliver speed, and numbers of mechanics were all independent variables. Table 8 shows the results of a linear regression. MMH required is regressed on reliability, repair capability, spare parts deliver speed, and the number of mechanics at Auto Front as shown in the following equation:

MMH Required ~ Reliability + Repair Capability + Spare Parts Delivery Speed + Number of Mechanics at AutoFront (CABs 1-3)

The coefficients of reliability, repair capability, and spare parts delivery speed are all negative and significant. This indicates that high repair capability and slower parts delivery lead to reduced maintenance on average. An analysis of variance showed that the effects of spare parts delivery speed and repair capability were significant with F (1,104), p<.001 and F (1,170), p<.001, respectively. A 1% increase in repair capability reduces MMH required by almost 6 hours, and there is an hour for hour decrease in MMH required for each hour delayed in parts delivery on average.

Dependent variable: MMH Required at Auto Front (CABs 1-3) (in hours)				
	Coeff	**Std. Error**	**t value**	**Pr(>|t|)**
(Intercept)	9.86	0.40	24.88	0.00
Reliability 1 (in miles)	0.33	0.13	2.59	0.01
Reliability 2 (in miles)	-0.31	0.13	-2.42	0.02
Repair Capability (in %)	-5.84	0.52	-11.18	0.00
Delivery (in hours)	-1.00	0.07	-14.32	0.00
AutoFront (in mechanics)	-0.01	0.00	-1.62	0.11
R-Squared	0.84			
Number of Observations	72			

Table 8. Regression Results for Maintenance Man-hours Required at AutoFront

Figures 13 through 15 support the classical regression modeling assumptions that the errors (residuals) be independent and normally distributed with mean equal to zero and have constant variance. Figure 13 is a plot of the

residuals vs. the fitted response. It displays constant variance and suggests that there are no obvious model defects. Figure 14 is a normal probability plot of the residuals and it shows that the residuals are approximately normal. Figure 15 displays the actual (MMH Required) vs. the fitted response.

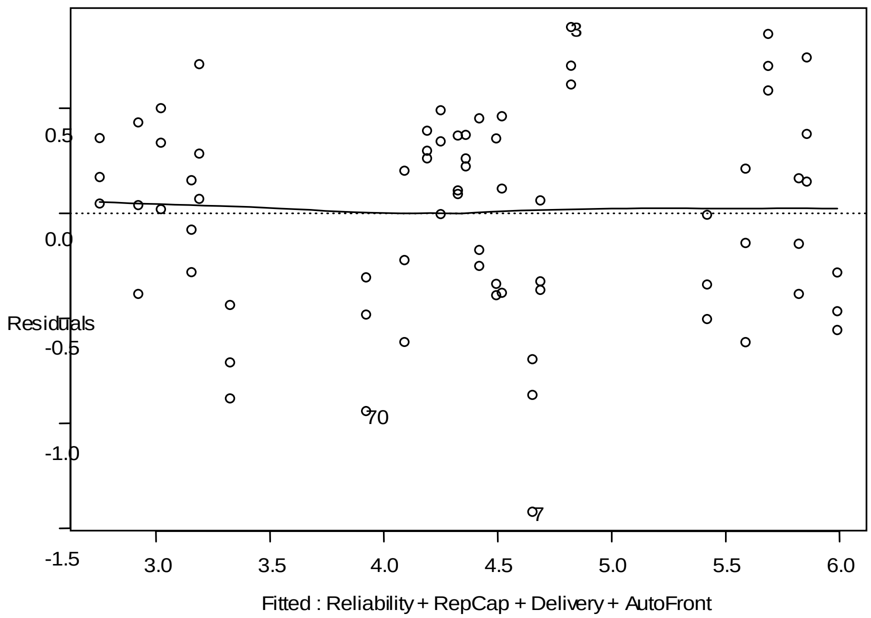

Figure 13. Residuals vs. Fitted Values for Maintenance Man-hours Required at AutoFront

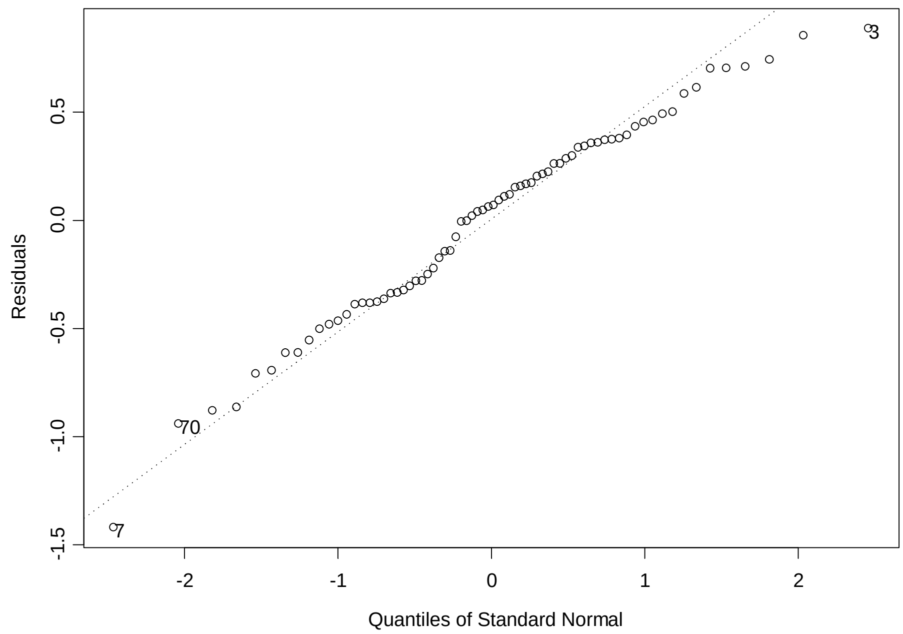

Figure 14. Normal Probability Plot of Residuals for AutoFront

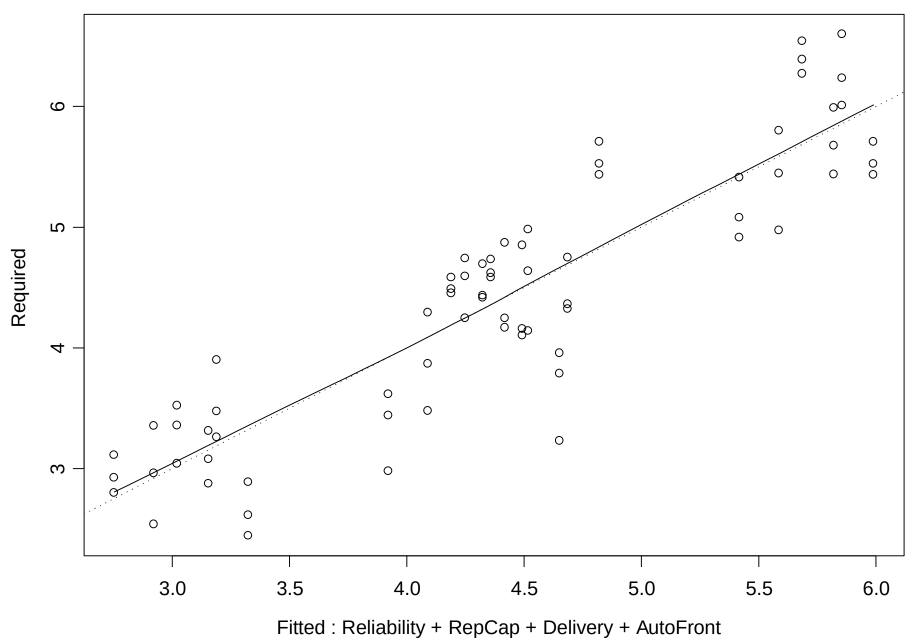

Figure 15. Actual vs. Fitted at AutoFront

2. AutoRear MMH

In this specification, MMH associated with the rear combat repair team's auto mechanics was the dependent variable and the same regressors from the previous specification were used so that the equation is a as follows:

MMH Required ~ Reliability + Repair Capability + Spare Parts Delivery Speed + Number of AutoRear mechanics.

Dependent Variable: MMH Required at AutoRear (in hours)				
	Value	**Std. Error**	**t value**	**Pr(>|t|)**
(Intercept)	132.47	6.94	19.10	0.00
Reliability1(in miles)	-13.39	1.14	-11.76	0.00
Reliability2 (in miles)	-10.15	0.66	-15.44	0.00
Repair Capability (in %)	-6.79	9.30	-0.73	0.47
Delivery (in hours)	-28.87	1.24	-23.29	0.00
AutoRear (no of mechanics)	-0.02	0.03	-0.54	0.60
R-Squared	0.98			
No. of Observations	24			

Table 9. Regression Results for Auto Rear

The coefficients of the regressors are all negative; however, only reliability and spare parts delivery speed are significant. An hour increase in spare parts delivery speed is associated with a 29- hour decrease in MMH on average. In any case, the residual plots for AutoRear showed obvious defects in the model. Figure 16, a plot of the residuals vs. the fitted suggests nonlinearity. Figure 17, the actual response vs. the fitted response, shows a slight departure near the lower left portion of the chart.

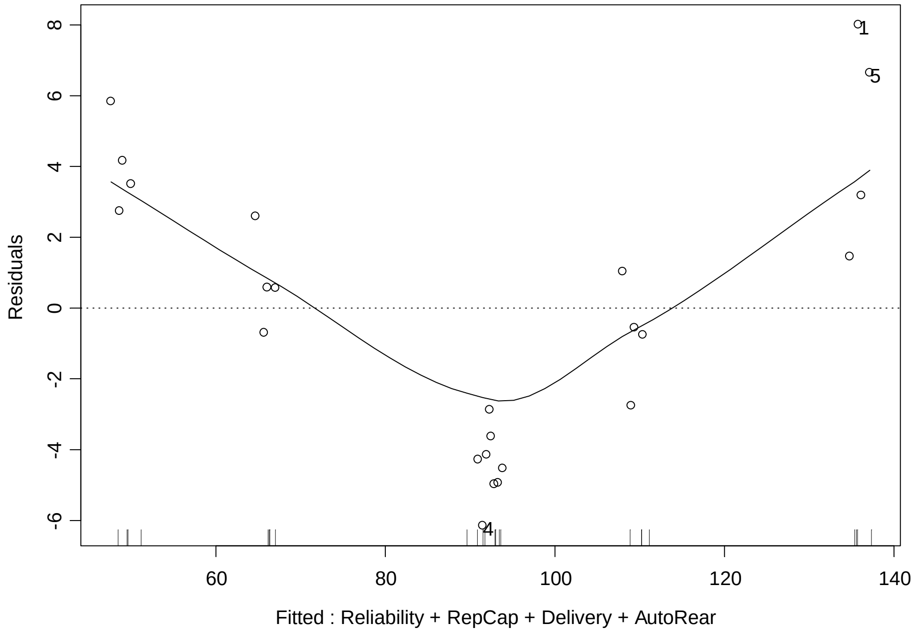

Figure 16. Residual vs. Fitted for Maintenance Man-hours Required at AutoRear

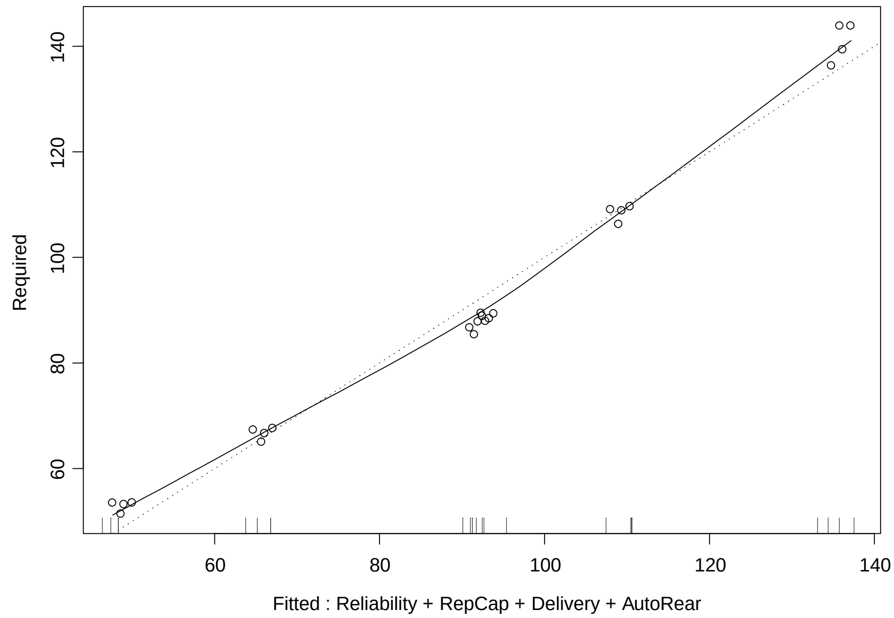

Figure 17. Actual vs. Fitted for AutoRear

Adding interaction between the regressor variables reliability and spare parts delivery speed makes the assumption of linearity for the AutoRear data more plausible. The following equation shows the additional interaction term:

Required MMH ~ Reliability + Repair Capability + Spare Parts Delivery Speed + Number of Mechanics + Reliability*Spare Parts Delivery Speed. See results of the regression in Table 10. Figures 18 through 20 display the residual vs. fitted, actual vs. fitted, and normal probability plot of the AutoRear MMH Required data after adding the interaction term.

Dependent variable: MMH Required at Auto Rear (in hours)				
	Coeff	Std. Error	t value	Pr(>|t|)
(Intercept)	132.47	2.72	48.71	0.00
Reliability1 (in miles)	-18.05	0.87	-20.79	0.00
Reliability2 (in miles)	-13.54	0.50	-27.01	0.00
Repair Capability (in %)	-6.79	3.65	-1.86	0.08
Delivery of Spares (in hours)	-28.87	0.49	-59.39	0.00
AutoRear (no of mechanics)	-0.02	0.01	-1.37	0.19
Reliability1*Delivery	3.72	0.60	6.25	0.00
Reliability2*Delivery	2.71	0.34	7.87	0.00
R-Squared	0.9974			
No of Observations	24			

Table 10. Regression Results for MMH Required at Auto Rear (after interaction term added)

An analysis of variance revealed that all of the regressors except the number of mechanics in the rear combat repair team were significant. Reliability and spare parts delivery speed had the highest F values, F (2, 1224) and F (1, 3527) respectively, with p <.001 for both regressors.

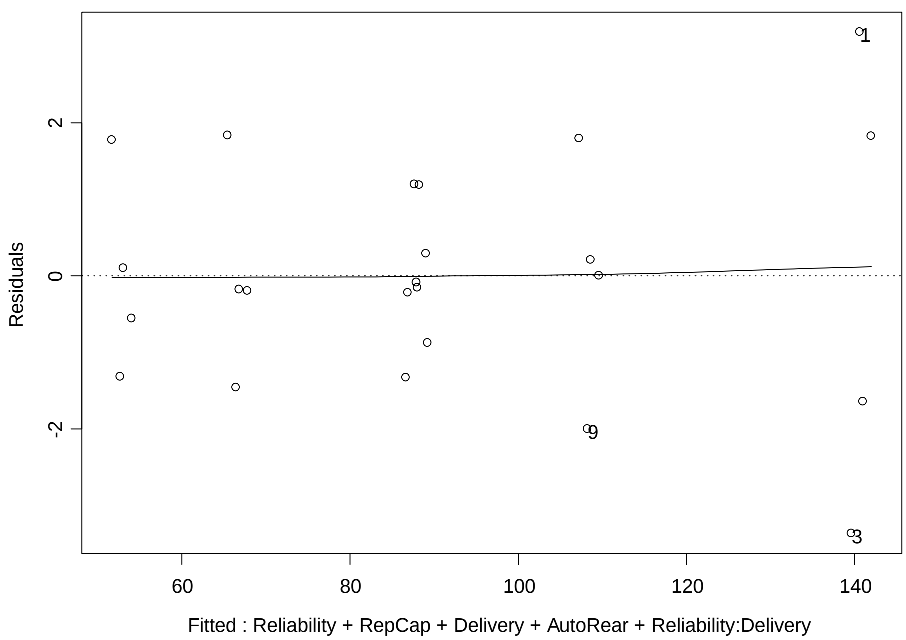

Figure 18. Residual vs. Fitted after Adding Interaction

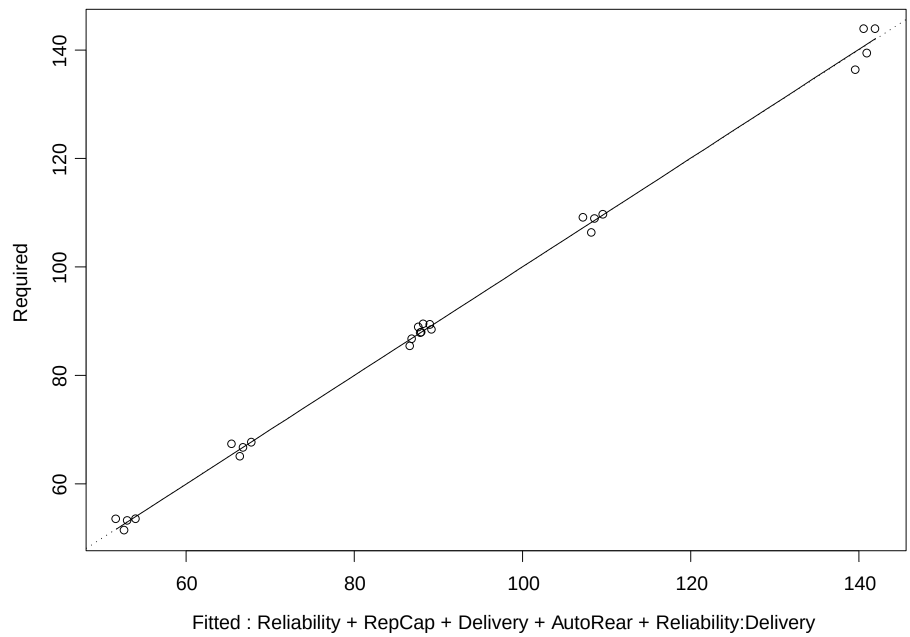

Figure 19. Actual vs. Fitted after Adding Interaction

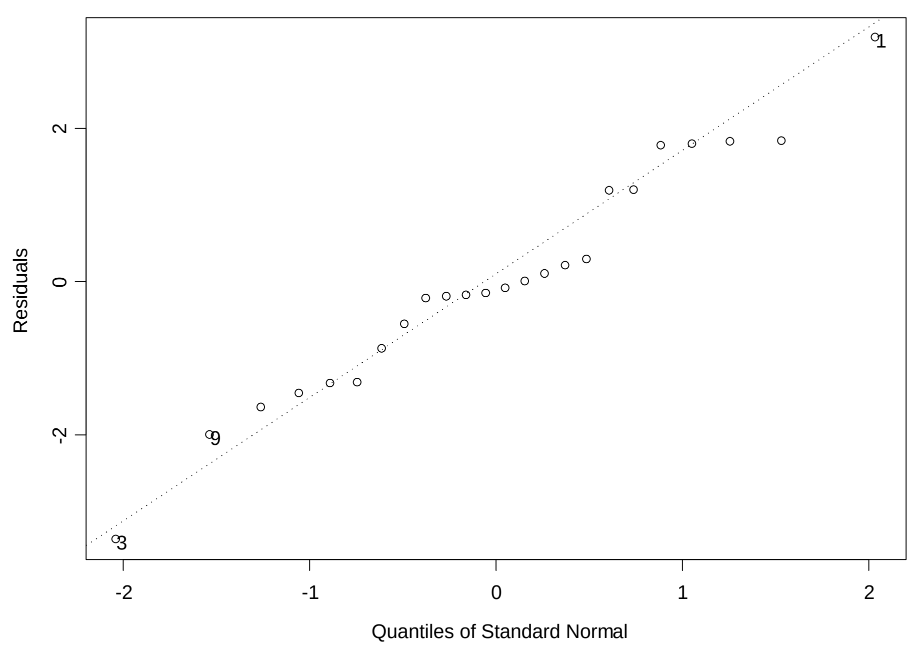

Figure 20. Normal Probability Plot after Adding Interaction

3. CommFront MMH

For the CommFront data set, the MMH for the communications mechanics was the independent variable and the same regressors from the previous two specifications were used to produce the following equation: MMH Required ~ Reliability + Repair Capability + Spare Parts Delivery Speed + Number of Mechanics. MMH required is regressed on reliability, repair capability, spare parts delivery speed, and number of communications mechanics in the front brigade's combat repair team.

Dependent variable: MMH Required at CommFront (in hours)				
	Value	**Std. Error**	**t value**	**Pr(>|t|)**
(Intercept)	2.47	0.18	14.05	0.00
Reliability 1 (in miles)	-0.26	0.06	-4.67	0.00
Reliability 2 (in miles)	0.34	0.06	6.10	0.00
Repair Capability (in %)	-1.99	0.23	-8.69	0.00
Delivery of Spares (in hours)	-0.13	0.03	-4.17	0.00
CommFront (no of mechanics)	-0.01	0.01	-1.27	0.21
R-Squared	0.76			
No. of Observations	72			

Table 11. Regression Results for MMH Required at CommFront

The coefficients of reliability, crew repair capability, and spare parts delivery speed are all negative and significant. The number of communications mechanics in the front brigades is not significant. An hour increase in the spare parts delivery speed leads to almost 8 minutes (0.13 *60 minutes) reduction in MMH on average. Additionally, a 1% increase in repair capability leads to a 2 hour reduction in MMH on average.

An analysis of variance showed that reliability and repair capability ranked higher in terms of significance than spare parts delivery speed. The F values for reliability (2, 32) and crew repair capability (1, 41) were three to four times that of spare parts delivery speed. The number of communications mechanics in the first three combat repair teams was not significant, F (1, .9), p < .35.

Figures 21 and 22 are plots of the residual vs. fitted and the actual vs. fitted for MMH required at CommFront. To address the inequality of variance displayed in Figure 21, a transformation on the response variable was employed, and the following equation was produced:

log (MMH Required) ~ Reliability + Crew Repair Capability + Spare Parts Delivery Speed + Number of mechanics at CommFront. Figures 23-25 show the plots of residual vs. fitted, actual vs. fitted, and normality probability for the transformed response.

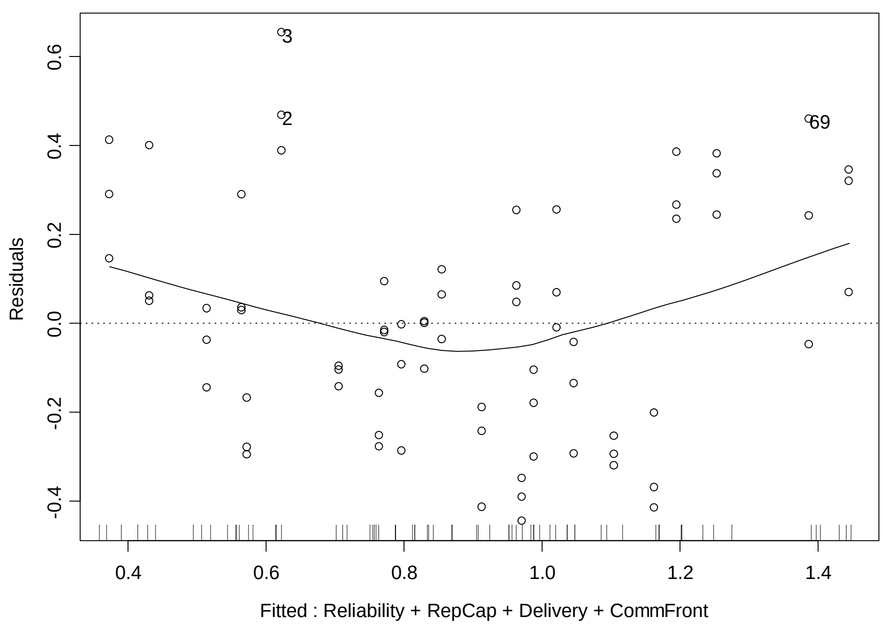

Figure 21. Residual vs. Fitted for CommFront

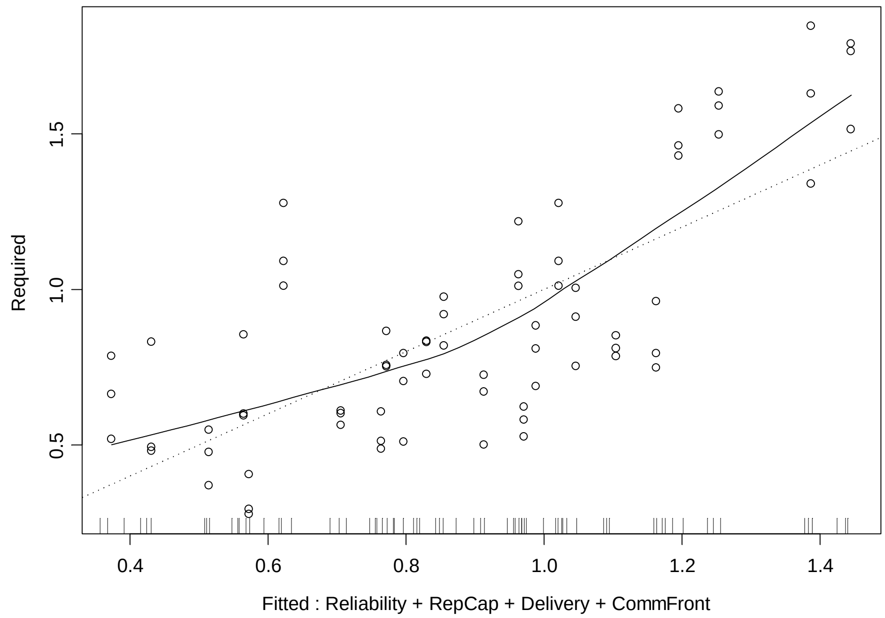

Figure 22. Actual vs. Fitted for CommFront

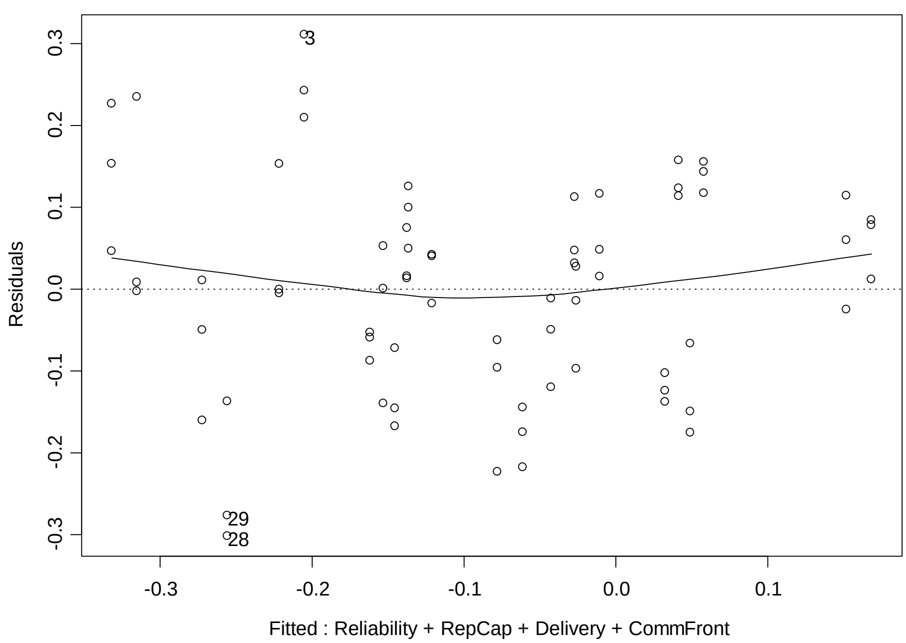

Figure 23. Residual vs. Fitted after Log Transformation

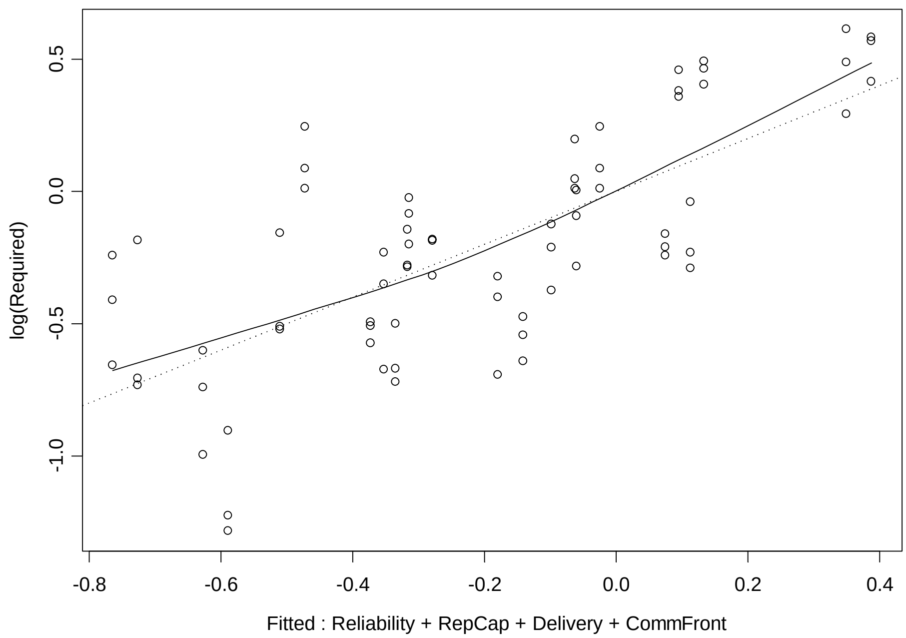

Figure 24. Actual vs. Fitted after Log Transformation

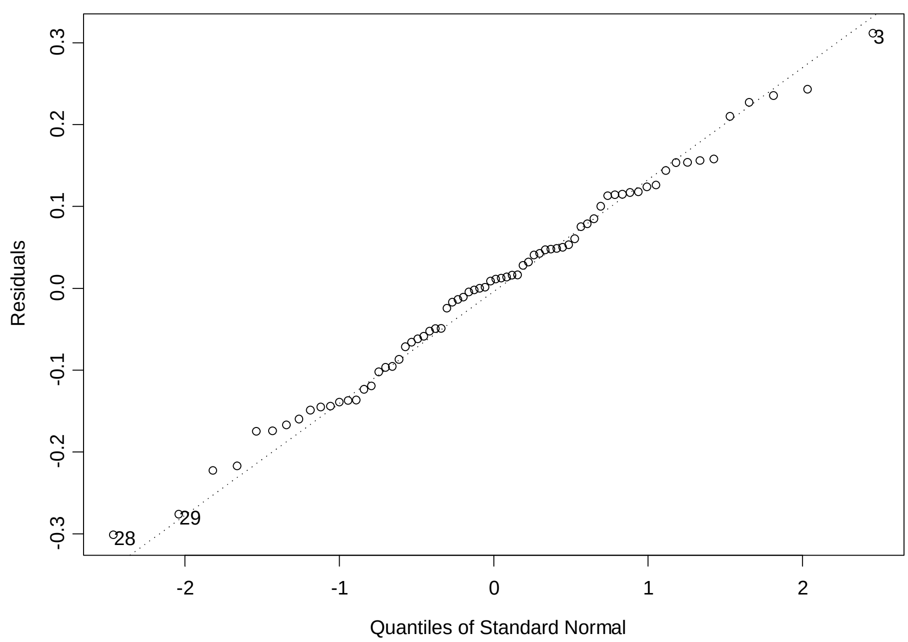

Figure 25. Normal Probability Plot after Log Transformation

4. CommRear MMH

In this specification, the MMH by communications mechanics in the rear combat repair team was the response and the same regressors from the previous specifications were used to produce the following equation:

MMH Required ~ Reliability + Crew Repair Capability + Spare Parts Delivery Speed + Number of mechanics at CommRear.

Dependent variable: MMH Required at CommRear (in hours)				
	Value	**Std. Error**	**t value**	**Pr(>|t|)**
(Intercept)	15.82	1.71	9.27	0.00
Reliability1 (in miles)	-2.77	0.28	-9.87	0.00
Reliability2 (in miles_	-2.04	0.16	-12.60	0.00
Repair Capability (in %)	-4.88	2.29	-2.13	0.05
Delivery of Spares (in hours)	-2.61	0.31	-8.55	0.00
CommRear (no of mechanics)	-0.02	0.04	-0.45	0.66
R-squared	0.95			
No. of Observations	24			

Table 12. Regression Results for MMH Required at CommRear

The coefficients of the regressors are all negative, and all of the regressors are significant except the number of communications mechanics in the rear combat repair team. An hour increase in spare parts delivery speed results in a 3 hour decrease in MMH on average. A 1% increase in crew repair capability results in a 5 hour reduction in MMH on average.

An analysis of variance revealed that reliability with F (2,128) and spare parts delivery speed with F (1, 73) were ranked higher in terms of significance than the other regressors. Both had p values less than .001.

Figure 26, the residual vs. fitted plot, indicates defects in the model. Figures 27 and 28 are further evidence of those defects. The flattened u-shape of the graph suggests non-linearity. After transforming the response variable using the log function, there was less evidence of non-linearity. Transforming the response variable resulted in the following equation:

Log (MMH Required) ~ Reliability + Crew Repair Capability + Spare Parts Delivery Speed + Number of mechanics. See Figures 29 and 30.

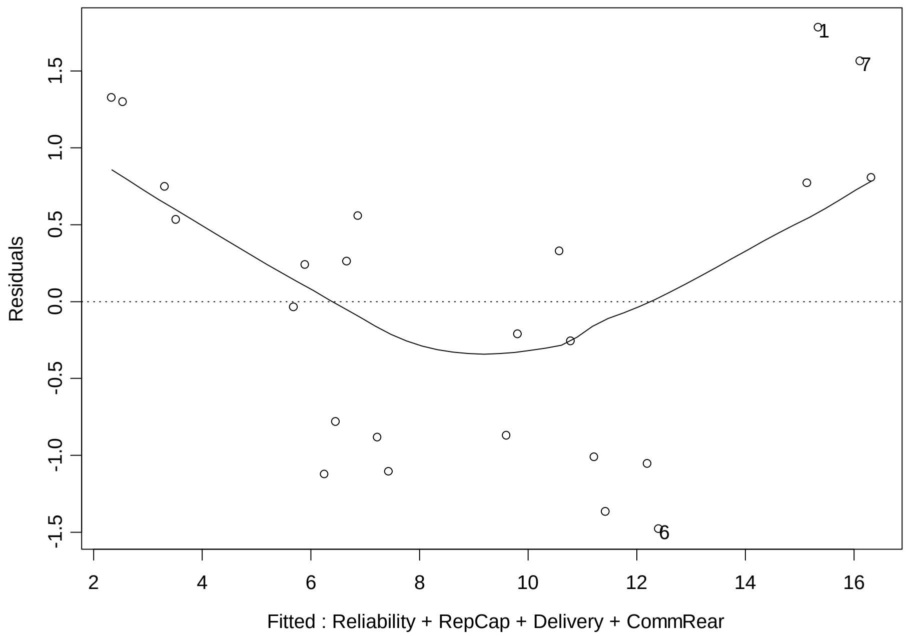

Figure 26. Residual vs. Fitted for CommRear

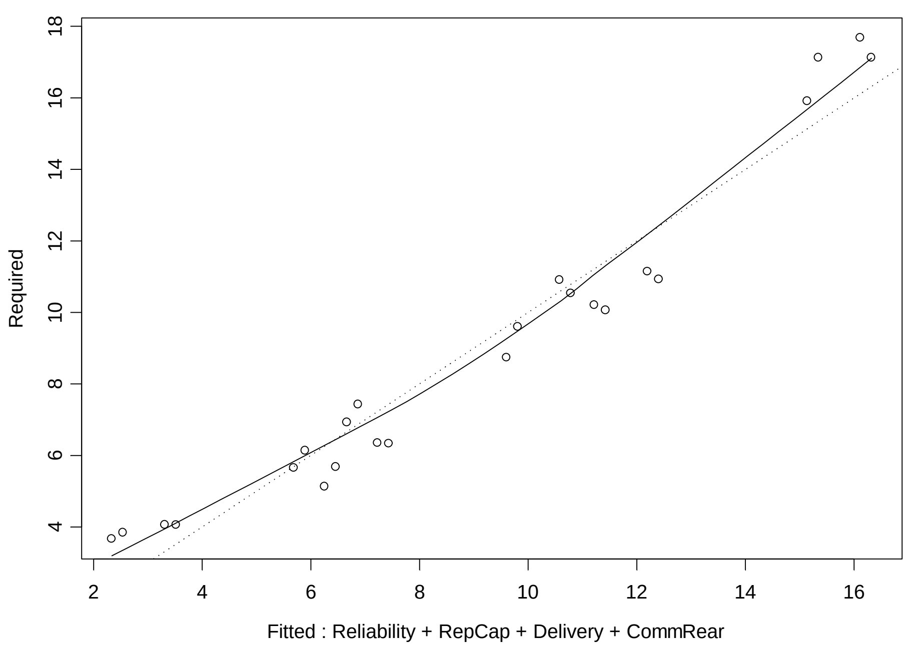

Figure 27. Actual vs. Fitted for CommRear

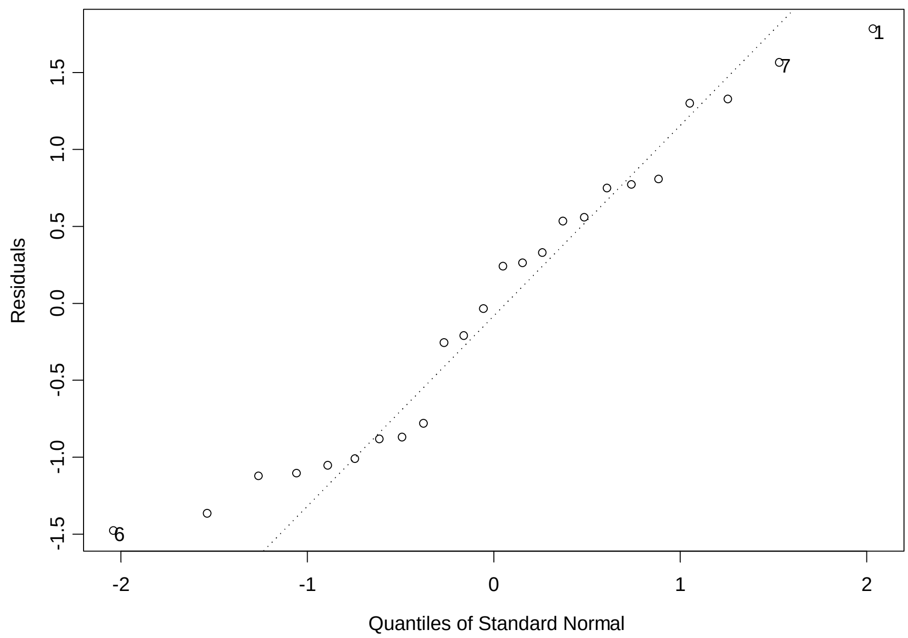

Figure 28. Normal Probability Plot of CommRear

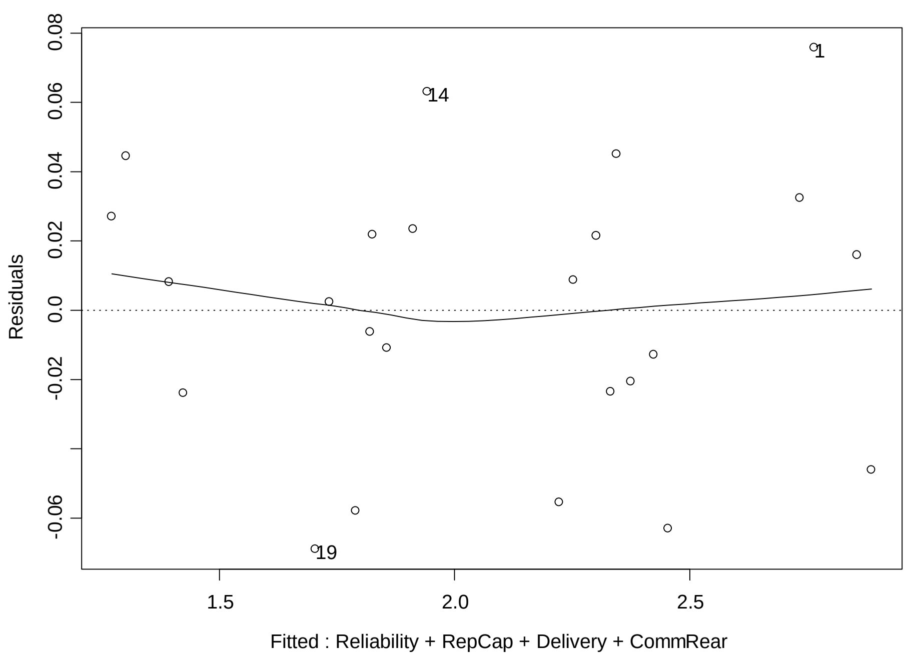

Figure 29. Residual vs. Fitted for CommRear after transformation

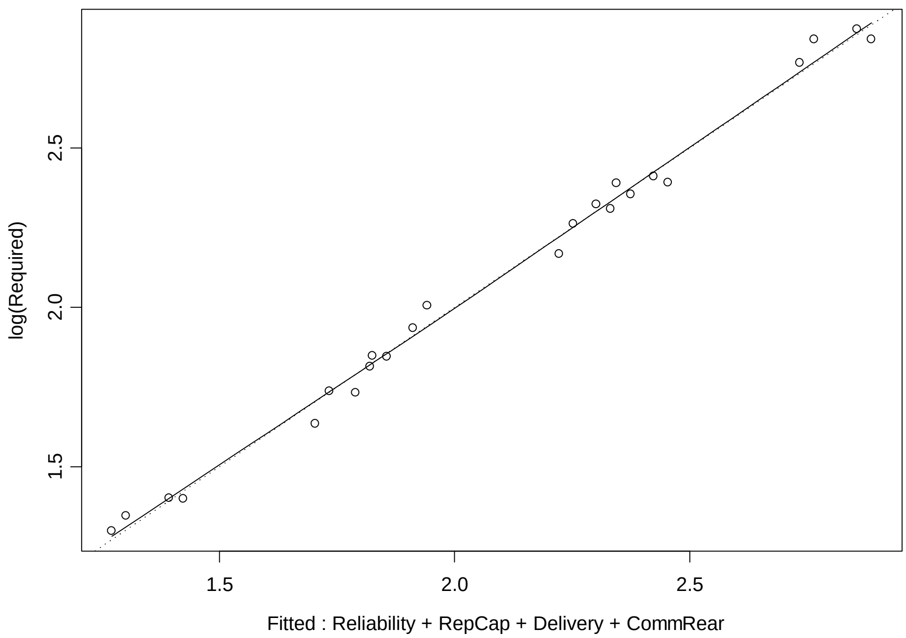

Figure 30. Actual vs. Fitted Plot of Residuals for CommRear after transformation

IV. DISCUSSION

This study found clear effects of the spare parts delivery speed, crew repair capability and system reliability on MMH required during a 72-hour scenario: with slower parts delivery, higher crew repair capability, and more reliable systems, there tend to be fewer MMH required. When there are more systems, as in the case of the rear combat arms brigade, there also tends to be more maintenance required. Additionally, the four factors used in this study were all generally good predictors of MMH.

As a modeling tool, DS mimics a real-world maintenance environment. It simulates the number of MMH required resulting from varying levels of crew repair capability, system reliability, spare parts delivery speed, and mechanics and presumably could be used to gain insight into real-world operations.

This study did not consider the impact of combat damage on MMH required. Future studies should. DS could be used to project maintenance requirements in a combat scenario. A recent Washington Post article reports an alarming amount of equipment needing repair that is currently being shipped back from Iraq. According to the article, “530 M1 tanks, 220 M88 wreckers, and 160 M113 armored personnel carriers are sitting at Anniston [an army repair depot]” [29]waiting to be repaired. The report goes on to report that “The Red River Army Depot in Texas has 700 Bradley Fighting Vehicles and 450 heavy and medium-weight trucks, while more than 1,000 Humvees are awaiting repair at the Letterkenny Army Depot.”[30] Much of the equipment is being used at five to ten times the normal peace time rates.

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[29] Tyson. A. “U.S. Army Battling To Save Equipment: Gear Piles Up at Depots, Awaiting Repair,” *Washington Post,* December 5, 2006; p. A01.

[30] Ibid.

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APPENDIX A. ACRONYMS

ARV	Armed Robotic Vehicle
AMSAA	Army Materiel Systems Analysis Activity
ANOVA	Analysis of Variance
AoA	Analysis of Alternatives
ARCIC	Army Capabilities Integration Center
C2V	Command and Control Vehicle
CAB	Combined Arms Brigade
CRT	Combat Repair Team
CASTFOREM	Combined Arms Support Task Force Evaluation Model
DS	Dynamic Sustainment
EFF	Essential Function Failure
FCS	Future Combat Systems
FMTV	Family of Medium Tactical Vehicles
FRMV	FCS Recovery and Maintenance Vehicle
HEMTT	Heavy Expanded Mobility Tactical Truck
HMMWV	High Mobility Multipurpose Wheeled Vehicle
ICV	Infantry Combat Vehicle
KPP	Key Performance Parameter
MMBF	Mean Miles Between Failures
MMH	Maintenance Man-hour
MTBF	Mean Time Between Failures
MULE	Multifunction Utility/Logistics and Equipment Vehicle
MCS	Mounted Combat System
MV-E/T	Medical Vehicle-Evacuation/Treatment
NEFF	Non Essential Function Failure
NLOS-C	Non-Line-Of-Sight Cannon
NLOS-M	Non-Line-Of-Sight Mortar
OMS-MP	Operational Mode Summary/Mission Profiles
OPTEMPO	Operational Tempo
OSD	Office of the Secretary of Defense
RSV	Reconnaissance and Surveillance Vehicle
SA	System Abort
TRAC	TRADOC Analysis Center
TRAC-FLVN	U.S. Army TRAC Ft. Leavenworth, KS
TRAC-LEE	U.S. Army TRAC Ft. Lee, VA
TRAC-WMSR	U.S. Army TRAC White Sands, NM
TRADOC	U. S. Army Training and Doctrine Command
VIC	Vector in Commander

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APPENDIX B. ADDITIONAL ANALYSIS OF MAINTENANCE MAN-HOURS DATA

A. ADDITIONAL PLOTS OF MAINTENANCE MAN-HOUR DATA

MMH required is the sum of MMH in progress, MMH delayed, and MMH performed. The following equation represents the relationship.

MMH required = MMH In progress + MMH Delayed + MMH Performed

When DS generates a maintenance man-hour output file, data MMH required, delayed, in progress, and performed is included. The following charts display the additional analysis which can be performed using DS.

1. MMH Required for Auto and Communications Mechanics at both the Front and Rear brigades

Figures 31 through 33 chart the MMH required for auto and communications mechanics at the front brigades (brigades 1-3) and the rear brigade. Note the pattern in the graph. Although not as prominent as the auto mechanics at the rear brigade chart (Figure 12, Analysis section), there is still evidence of a difference between the odd- and even-numbered treatments. For example, within treatments 1-8, the even-numbered treatments are consistently less than those odd-numbered treatments in their vicinity. Refer to Table 7 for the treatments used.

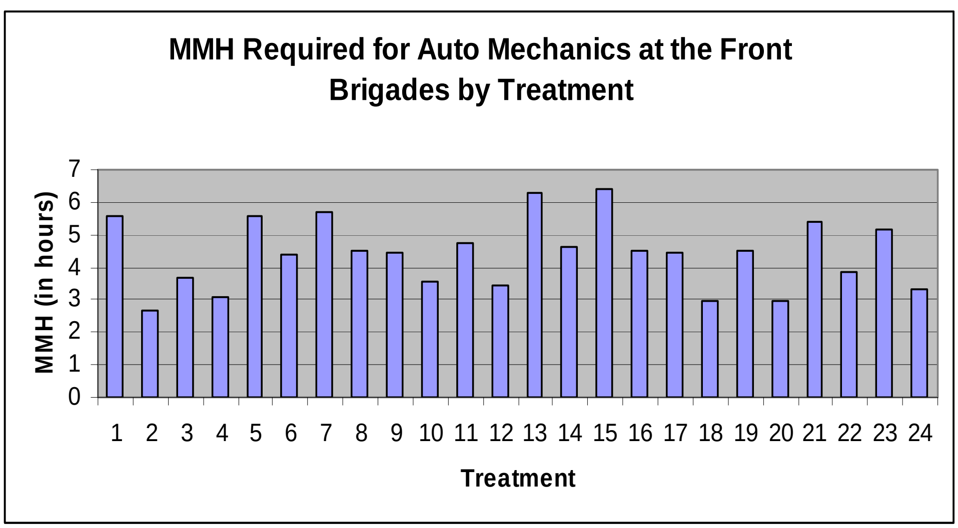

Figure 31. MMH Required for Auto Mechanics at the Front Brigades by Treatment

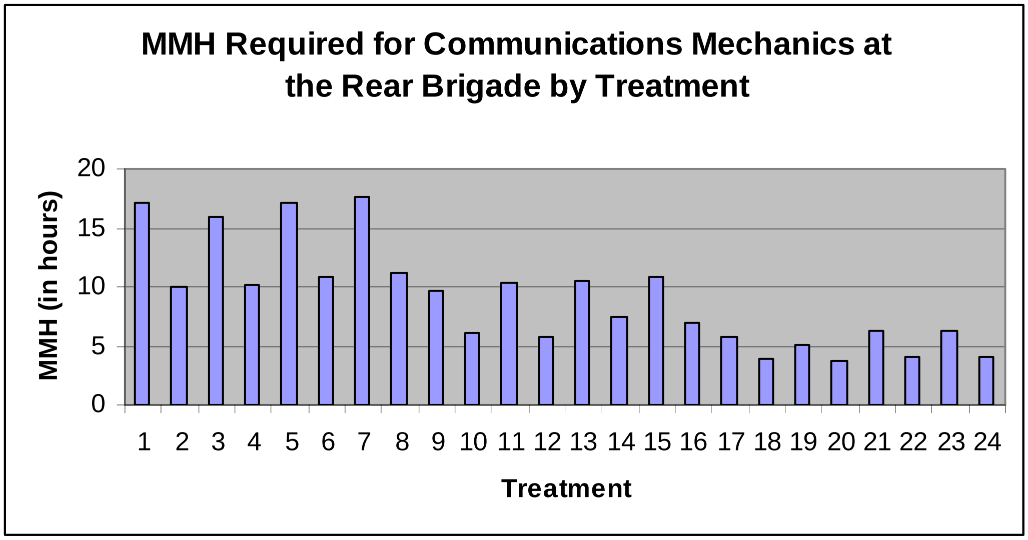

Figure 32. MMH Required for Communications Mechanics at the Rear Brigade by Treatment

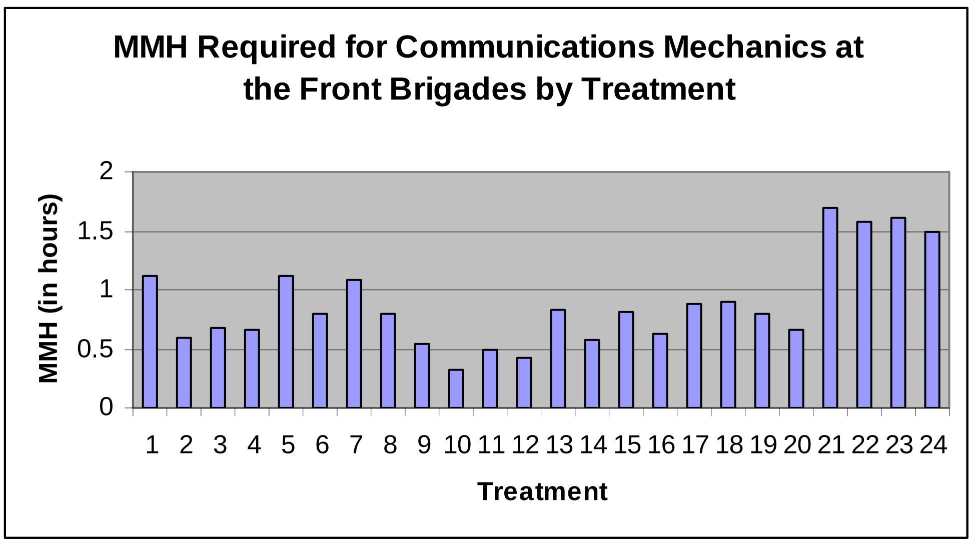

Figure 33. MMH Required for Communications Mechanics at the Front Brigades By Treatment

2. MMH Delayed for Auto and Communications Mechanics in the Front Brigades

Figures 34 and 35 show the average MMH delayed for the mechanics at the front and rear brigades. The most delayed MMH are the 6 minutes (.1 hour, see Figure 34) experienced by the auto mechanics in the front brigades. There are several treatments which do not generate delayed MMH. For the

communications mechanics at the front brigades, this number is higher, nearly 24 minutes (.4 hour, see Figure 35).

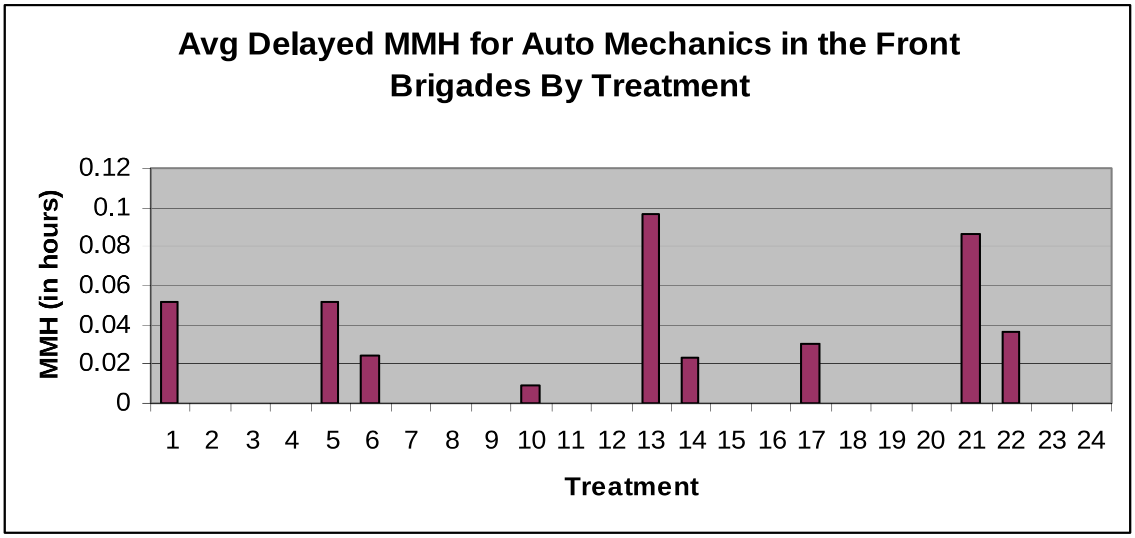

Figure 34. Average Delayed MMH for Auto Mechanics in the Front Brigades by Treatment

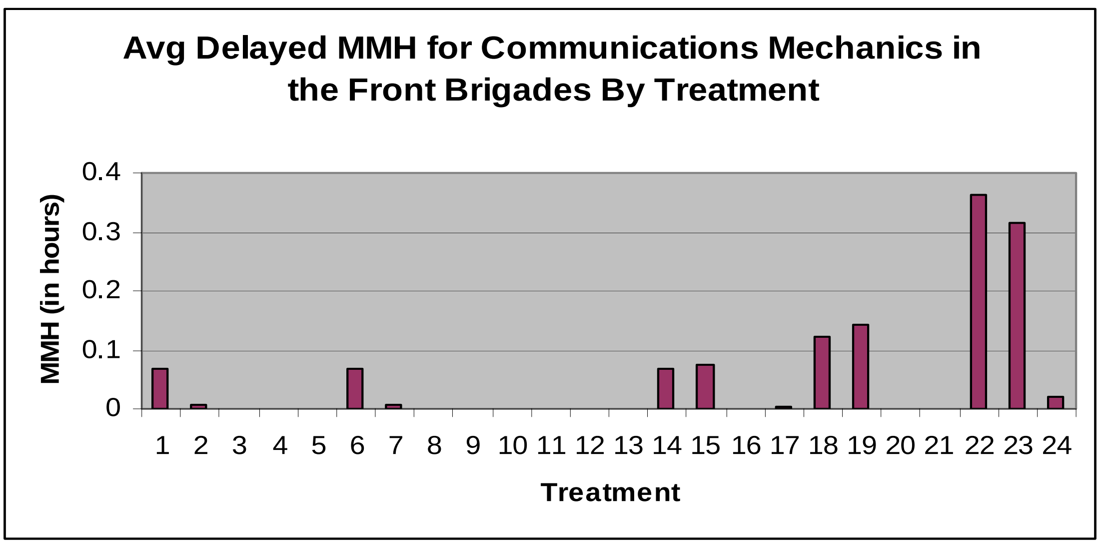

Figure 35. Average Delayed MMH for Communications Mechanics in the Front Brigades by Treatment

3. MMH In Progress for Auto and Communications Mechanics at both Rear and Front Brigades.

Figures 36 and 37 display the MMH in progress for auto and communications in the front and rear brigades. Treatment 15 (just over 5 hours) produces the most In Progress MMH for auto mechanics in the front brigade. Treatment 23 produces the most MMH for communications mechanics at the front brigades.

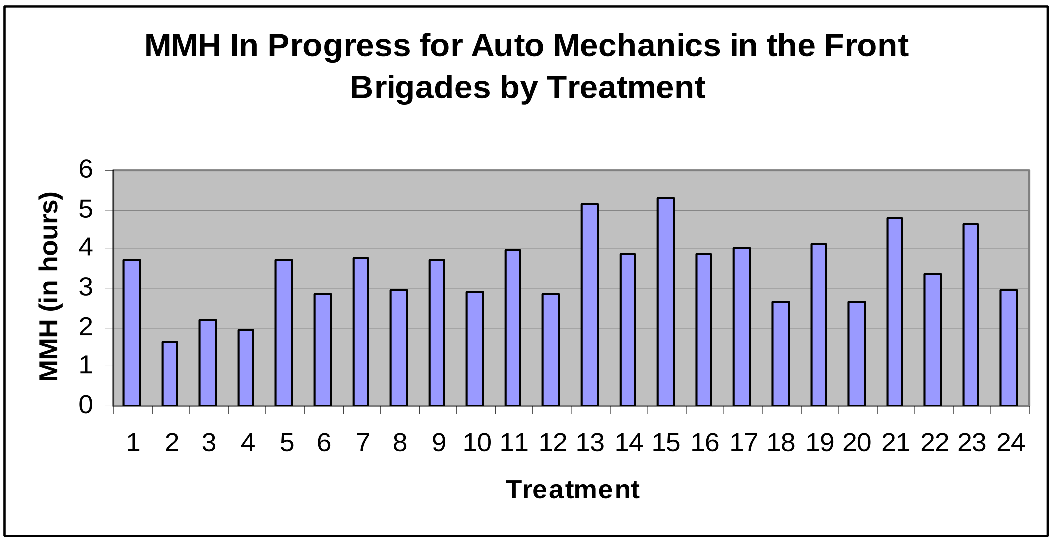

Figure 36. MMH In Progress for Auto Mechanics in the Front Brigades by Treatment

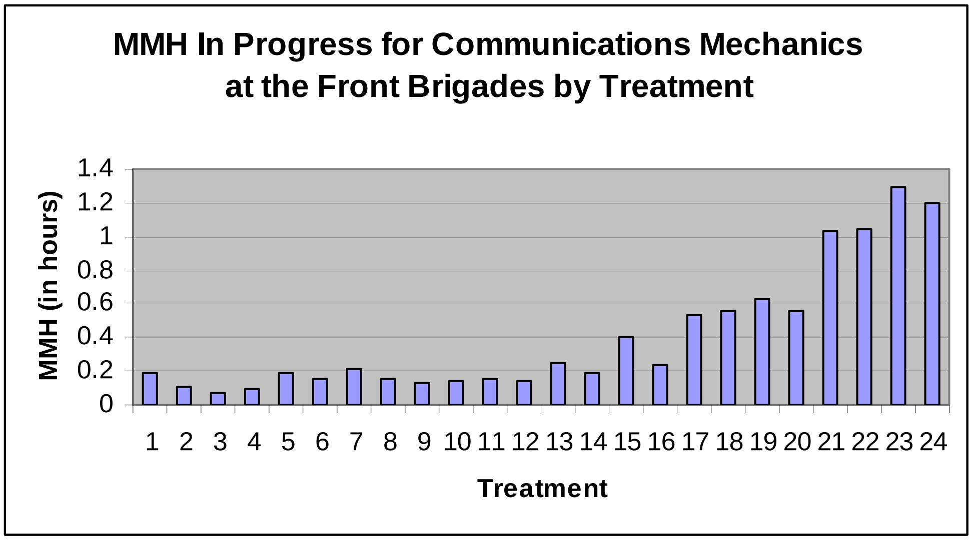

Figure 37. MMH In Progress for Communications Mechanics at the Front Brigades by Treatment

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APPENDIX C. STUDY PRIMER

A. DEPARTMENT OF DEFENSE ACQUISITION PROCESS

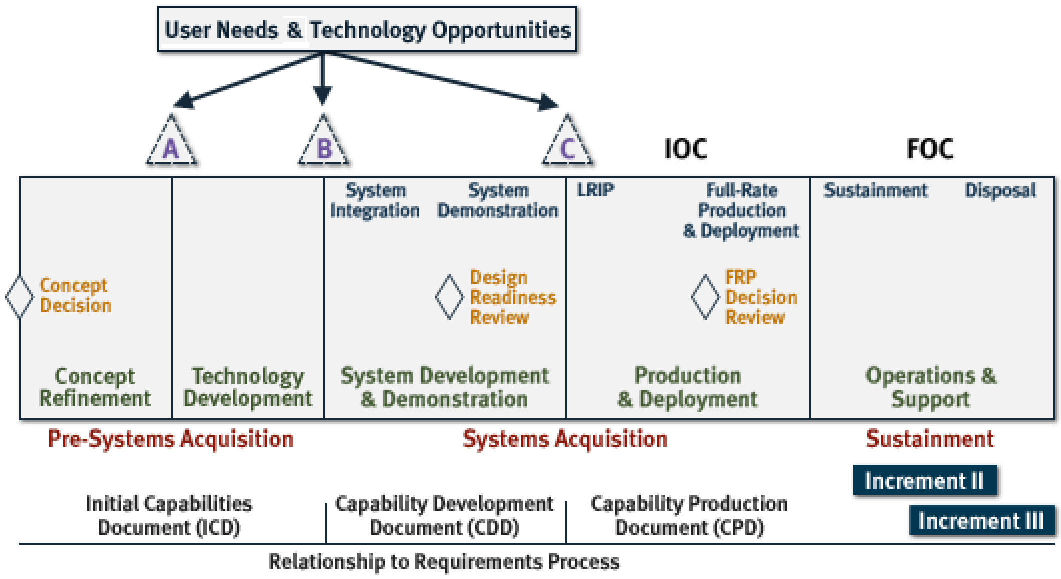

Figure 38. Defense Acquisition Management Framework[31]

The Defense Acquisition Process attempts to obtain quality products that meet user needs while simultaneously improving mission capability and operational support. The following key terms help illuminate the process outlined in Figure 23. [32]

Defense Acquisition Management Framework – consists of Milestones, Phases, and Efforts in the Defense Acquisition Lifecycle. Progress through the Defense Acquisition Lifecycle depends on obtaining adequate information to advance to the next stage of development. The Milestone Decision Authority can grant permission to start the acquisition system at any point in the framework as long as it is consistent with phase-specific entrance criteria and statutory requirements.

31 Defense Acquisition Process Tutorial [http://akss.dau.mil/darc/TUTORIAL/index.htm.] December 9, 2006.

32 The information on the Defense Acquisition Process is adapted from the Defense Acquisition Process Tutorial. [http://akss.dau.mil/darc/TUTORIAL/index.htm.] December 9, 2006.

The framework is divided into three activities: Pre-Systems Acquisition; Systems Acquisition; and Sustainment. The activities are divided into five phases: Concept Refinement, Technology Development; System Development & Demonstration; Production & Deployment; and Operations & Support. The phases that make up Systems Acquisition and Sustainment are divided into six efforts: System Integration; System Demonstration; Low-Rate Initial Production (LRIP); Full-Rate Production & Deployment; Sustainment; and Disposal.

Milestone Decision Authorities (MDAs) – those persons given authority under criteria established by the Under Secretary of Defense (Acquisition, Technology, & Logistics) (USD(AT&L)), or by the Assistant Secretary of Defense (Networks and Information Integration) ASD(NII) for AIS programs, to advance acquisition programs into the next phase of the acquisition process.

Program Managers (PMs) – those persons given authority under criteria established by the appropriate Component Acquisition Executive to oversee an acquisition program.

Initial Capabilities Document (ICD) - details capability gaps in joint warfighting functions. The ICD records previous studies of materiel approaches suggested to meet the capability need. The ICD also suggests a recommended materiel approach based on analysis of the different options under consideration. The ICD offers input on how the recommended approach best satisfies the intended joint capability.

Analysis of Alternatives (AoA) – illuminates the decision process highlighting the risks, advantages, and disadvantages of all materiel approaches under consideration. The AoA process includes sensitivity analysis of each materiel approach.

Technology Development Strategy (TDS) – details the scheme for achieving the Technology Development Phase. The TDS provides a detailed plan which includes the cost, schedule, and performance goals for research and development.

Capability Development Document (CDD) - The CDD holds the operational performance parameters, including Key Performance Parameters (KPPs), required by the acquisition community to design a proposed system and establish a program baseline. The CDD is heavily influenced by the Initial Capabilities Document (ICD), the Analysis of Alternatives (AoA), and the Technology Development Strategy (TDS).

B. EXISTING ARMY MODELS

1. Vector in Command (VIC)[33] VIC is a computerized, analytical, mid-intensity model developed to estimate net assessments and force deployment studies and to complete sensitivity analysis of weapon systems. The model can simulate any theater depending on the database.

2. CASTFOREM[34] is a stochastic, event-sequenced simulation model in which simulates opposing forces in ground combat. There are two modes of use for the model: batch or interactive. Additionally the model can represent combat support and combat service support units which interact with and affect the combat activities of forces.

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33 CACI Products Company Simulations and Modeling website. [http://www.simprocess.com/solutions/simscript_military_operations.cfm#CASTFOREM. December 9, 2006.

34 Ibid.

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